A robot-based inspecting system for 3D measurement

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***Abstract* — Zero Defect Manufacturing aims to minimize the number of defects within a process through proper measurement and control that make possible defect prediction and prevention. This procedure should ideally be performed in a non-destructive approach.**

Hence, this paper presents two novel non-destructive measurement systems for the geometric control of metal bars concerning a plant producing steel parts. The aforementioned systems are designed to be integrated into the actual process with minimum intervention supporting the online quality control of the manufactured product.

The two measurement systems exploit an industrial robotic manipulator and an optical sensor mounted on the robot's end effector. They differ in the strategy of motion of the laser line triangulation sensor relative to the steel part to be measured.

The proposed systems have been implemented as prototypes and deployed at the premises of a steel manufacturer to test and validate their performance, with the preliminary findings being provided and discussed in this work.

Keywords— Zero defect manufacturing, robot-inspection system, 3D measurements, 2D measurements, non-destructive inspection, Industry 4.0, in-line quality control, laser triangulation system

I. Introduction

Zero Defect Manufacturing (ZDM) concept overcomes conventional quality control approaches as Lean Production and Six Sigma and focuses on the almost total elimination of defects [1] [2].

This has been made feasible in recent years by the development of innovative information technology methods like data analytics, Artificial Intelligence (AI) and Machine Learning (ML), and new measurement and visualization procedures that have enabled distributed quality control and monitoring in industry [3] [4]. In the present days, manufacturing industries are attempting to reduce and minimize the amount of defects and errors within a process by improving not only the detection and correction of any anomalies in the finished product, but also by implementing measurement systems that make possible defect prediction and prevention [1] [4]. This concept allows to improve quality and reduce manufacturing costs [4].

The design and the implementation of the measurement system detailed in this paper is part of the European project named OpenZDM. The intent of OpenZDM is to define, along a production line, a set of Non Destructive Inspection (NDI) systems that can provide useful data for process monitoring, quality control and production process management.

This paper focuses on two measurement systems designed to perform geometric control of a metal bar to be applied in the production plant of VDL Weweler B.V. VDL Weweler B.V. develops, produces, tests, and sells air suspension systems, axle lift systems and parabolic springs from its high-tech fully automated plant in Apeldoorn (NL) [5]. VDL Weweler B.V. is strongly committed to implement ZDM in its production plants.

The two measurement systems presented in this work are part of what are known as 'robotic inspection systems'. These types of equipment consist of two elements, an industrial robot and an optical sensor mounted on the robot's end [6] [7].

The non-contact sensor is placed at the end of the robotic arm to exploit the wide flexibility that the robot has, thanks to its six Degrees of Freedom (DoF), in orienting the inspection system in different poses. This allows, depending on the application, to make fast measurements accomplished in few seconds, to take several images and generate , for example, 3D point cloud of the area of interest [8] [9]. This paper focuses on geometric measurements of steel bars.

The advantages of these inspection systems are first of all the chance to perform tasks, and activities in places that are not always physically reachable, but also to provide high precision quality control by a non-contact measurement system [10] [11].

In both measurement systems, exploited in this work, the hardware part consists of an industrial robot used as a scanning system, and a laser line triangulation sensor, plus a local pc for data acquisition, control, analysis and storage (Fig. 1). The triangulation system is made up of a camera and a laser diode that projects a line onto the object. This line is then detected by the camera and its coordinates are extracted so to measure a profile of the target along the line.

The first measurement method focuses on generating a point cloud on the full metal bar. The laser line triangulation sensor is mounted on the robot end effector. The measurement system acquires a series of profiles along the entire length of the bar from differen points of view in order to have a set of profiles for each bar side. Then, all these data are merged to obtain the point cloud describing the full 3D geometry of the bar. In this measurement system, the further challenge is the post-processing of the point clouds; in fact, filtering and segmentation tasks are required at first, and then specific algorithms are necessary to detect, identify and measure the geometry of the elements [12].

The second measurement system, also characterized by the laser line triangulation sensor mounted on the robot's end effector, moves the sensor to pre-programmed specific measurement positions in front of the object. In this way only 2D selected features of interest are measured [9]. The full 3D point cloud will not be generated. This method reduces the amount of data to be processed because only a small number of profiles are acquired, avoiding processing a huge number of data to generate a full 3D point cloud. In this way, not only the computational load of the postprocessing of the profiles is decreased considerably but also the acquisition time is significantly reduced. This is important to perform measurements within the constraints imposed by the takt time of the production line. Furthermore, the opportunity to investigate narrower regions allows the employment of sensors with a smaller working range with a subsequent improvement in the spatial resolution and associated measurement uncertainty.

The measurement accuracy of both the systems is determined not only by the triangulation system resolution and its respective algorithm, but also by the ability to position the robot at the specific point.

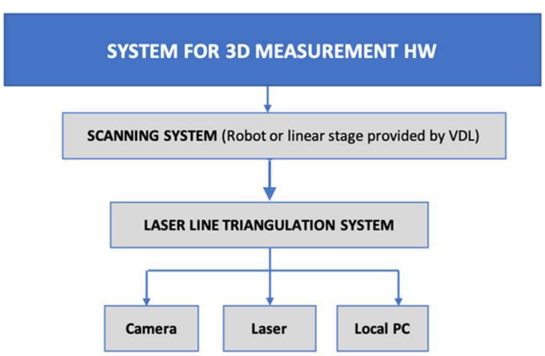

Fig. 1 System For 3d Measurement of trailing arm geometry – Hardware Architecture

The software (Fig. 2) is different for the two measurements system:

- for the 3D measurement system, the software is based on a 3D point cloud generation from the raw data profiles. Geometric measurements will then be feasible only by using specific software for point cloud managements;

- for the 2D dimensional measurement system, the software measures each selected feature directly from the raw profiles.

Once measurements are available, the software may perform conformity assessment and therefore provide a diagnosis necessary for ZDM.

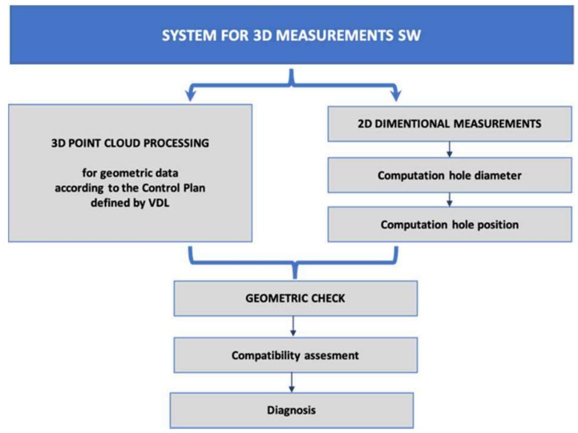

Fig. 2 System For 3D Measurement of trailing arm geometry – Software Architecture

II. Materials and Methods

A. *Laser line triangulation system for point clouds measurement*

The sensor used in the application is a laser line triangulation system, Gocator LMI 2350.

The laser wavelength is 650 nm. The laser minimum working distance is 300 mm and the measuring range is up to 700 mm. The nominal resolution, according to the specifications of the laser triangulation sensor, is 0.150 mm in y axis, and 0.019 mm in z axis (Fig. 3) that shows the cartesian system referred to the bar.

This laser triangulation system is fixed on the robot end effector and the scan is performed along the bar from different points of view (Fig. 3).

The robot used is an industrial robot, featured by 6 DoF.

The examined bar is about 1 m in length and 90 mm along the lateral side. According to the technical drawings provided by VDL Weweler B.V. the hole bar size is 13 mm with a tolerance of ± 0.5 mm.

While the robot moves, the laser scans the whole object from left to rigth moving along x axis. The robot movement is programmed so that the velocity is set to be constant and the trajectory is almost parallel to the analysed bar.

In this scenario, the acquisition depends not only on the laser performance, like the resolution along the y- axis, z-axis, but also on the robot velocity and its ability to follow a straight trajectory both in z-x plane and x-y plane.

The reference axes for this measurement procedure are defined as follow:

- x-axis referes to the scan direction along the major dimension of the trailing arm;

- y-axis coincides with the laser line;

- z-axis is the laser line triangulation sensor depth of field direction.

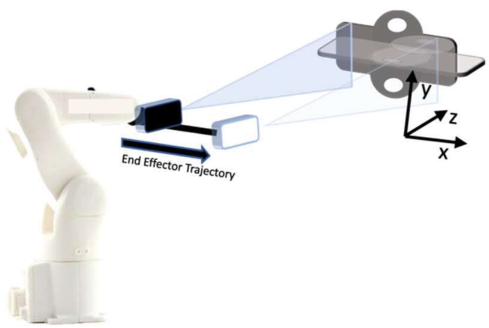

Fig. 3 Laser triangulation system on the robot end effector for 3D measurements

The measurement procedure consists of two steps: profile transversal acquisition along one side of the bar at first, and the following measurement repetition along all four sides of the bar. At each step, the bar should be rotated around the x-axis to acquire the four bar sides. For each side, the triangulation system must start and stop the acquisition according to a gate signal provided by the robot (Fig. 4). The profiles are acquired in internal trigger mode, within a time window provided by the robot through a gate signal. The gate provided by the robot should have a time length so that the scan length will be equal to the portion of the bar under measurement (L) (Fig. 5).

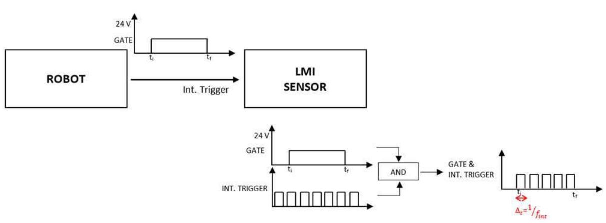

Fig. 4 Gate Signal Trigger block diagram

When the gate signal is high, the laser scanner works at its internal frequency (f_{int}) and generates laser profiles equally spaced of ΔL as given by (1):

$$\boldsymbol{\Delta L} = (V\ [mm/s])/(f\_int\ \ [Hz]\ ) \quad (1)$$

The number of profiles generated will depend on the scan length (L) and on the profiles distance (ΔL) as given by (2).

$$\boldsymbol{N} = \frac{L\ [mm]}{\Delta L\ [mm]} \quad (2)$$

This method will produce equally spaced transversal profile only if the robot velocity is constant.

By combining the profiles collected the by laser triangulation sensor, it is feasible to obtain a point cloud in which the resolution along x depends on ΔL and the resolution in z and y depends on the laser line triangulation system geometric design.

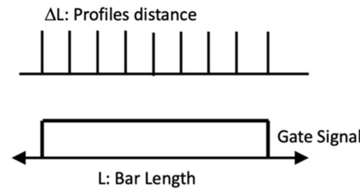

Fig. 5 Internal trigger of the laser line triangulatuion system (top plot) and gate signale provided by the robot (bottom plot)

By performing the scan on the other three bar sides it is possible to reconstruct the full 3D bar point cloud. The bar geometry reconstruction is performed by using a set of fiducials applied manually on the bar (Fig. 6). To improve the reconstruction accuracy each of the four points clouds must have overlapping regions to facilitate the merging operation.

Fig. 6 Artificial fiducials placed over the bar

Large part of the activity presented in this work is focused on the analysis of uncertainty sources that will influence the accuracy of the 3D point cloud reconstructed. The most important uncertainty source is the straigthness and repeatability of the robot trajectory. To quantify the trajectory straigthness deviation the laser line triangulation system has been made to scan over a straight reference bar at different speeds of the robot, so to check if the straigthness deviation depends on the speed. The robot speeds considered are 25 mm/s, 50 mm/s and 100 mm/s.

Referring to Fig. 7 showing the set of profiles acquired along the reference bar, the robot trajectory along z-x plane is detected by extracting one specific pixel in the y axis for the whole sequence of profiles in the x direction.

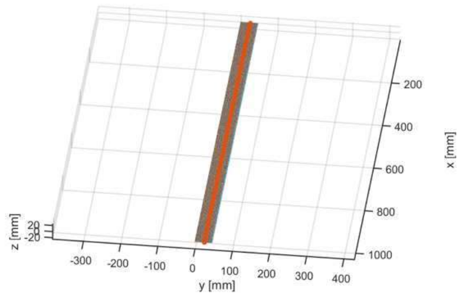

Fig. 7 Profiles acquired along the reference bar and the line extracted at one specific pixel in the x-direction (red dots)

The extracted bar profiles along the x-direction at the three robot speeds are shown in (Fig. 8) after having removed their mean value. These profiles represent the robot trajectory along the z-x plane.

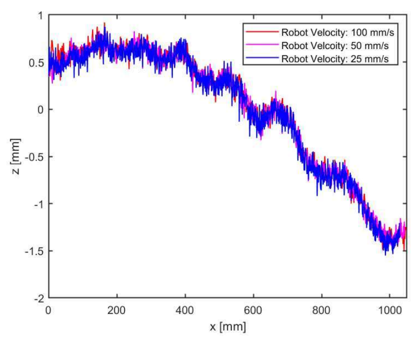

Fig. 8 Robot trajectory in z-x plane

Fig. 8 shows that the robot's trajectory is not straight and provides an estimatation of the deviation from a straigth line. By observing the measured trajectory plots it is visible that they can be fit by a combination of parabolic and sinusoidal trends. The deviation has then be calculated by performing an 8th order Fourier fit using as data the complete set of trajectories for the three robot speed. The fit result (red line) is plotted together with the trajectories at the three robot speed (blue dots) in Fig. 9.

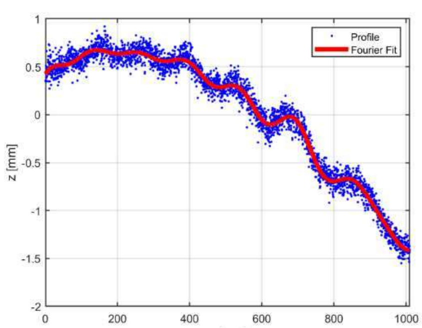

Fig. 9 Fourier fit performed on the trajectory in z-x plane for the three robot speeds

The residuals calculated between the Fourier fit and original distribution show a gaussian distribution (Fig. 10), with a standard deviation of 0.0792 mm. This represents the random part of the fluctuations of z(x).

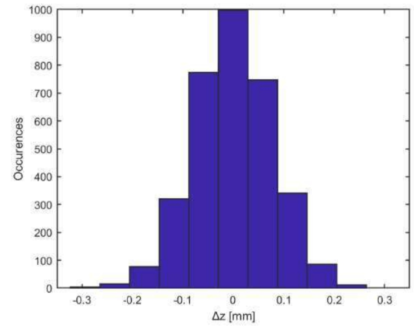

Fig. 10 Residuals distribution histogram

The trajectory analysis reports that the deviation from straigthness appears to be deterministic and repeatable and therefore it is possible to correct this deviation also in operation, i.e., when the measurement bar is scanned. In fact, the Fourier fit is exploited to correct the profiles acquired along the VDL Weweler B.V. bar from the different points of view and then the 3D point cloud is reconstructed.

Once the point cloud has been generated and its trajectory is corrected, the point cloud can be analyzed to extract geometric measurements. Considering one hole, a specific Region Of Interest (ROI) is selected around it (Fig. 11). In order to estimate the hole diameter, the points belonging to the inner region of the hole are manually picked out. These points are then fitted by a circle. The diameter of the fitted circle gives the hole size dimension.

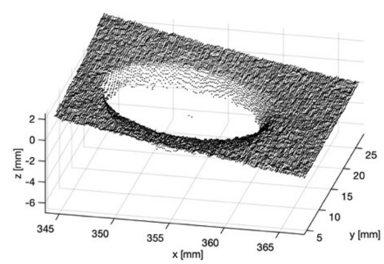

Fig. 11 Bar point cloud around a feature

B. *Laser line triangulation system for 2D features measurement*

The measurement system is made up of a laser line triangulation sensor, Wenglor MLSL 132, mounted on a robot end effector, VS6577 GM-B Denso Robot. The robot used is an anthropomorphic robot with 6 DoF.

The robotic arm is used to rotate the triangulation system through specific angles and perform targeted measurements, like the hole diameter or hole distance (Fig. 12).

The reference axes, for this 2D measures, are defined as follow:

- z-axis is the laser line triangulation sensor depth of field direction.
- x axis coincides with the laser line. Considering the hole size measure, a 2D axial symmetrical feature, this axis rotates around the z-axis by known amounts in order to take into account all necessary hole views.

The laser wavelength is 405 nm, the nominal resolution ranges from 33 to 47 µm in x axis, and from 4.8 to 9.6 µm in z axis. The laser working distance is 65 mm and the measuring range, in the x direction, is 60 mm.

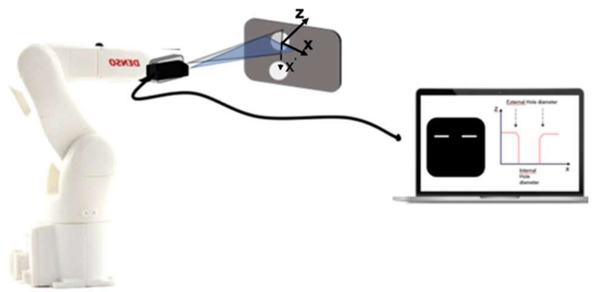

Fig. 12 Laser line triangulation system on the robot end effector for 2D geometric features measurement

In relation to the measurement of the hole diameter, a series of N profiles *z(x)* have been acquired, while the triangulation system rotates around the z axis. The hole diameter is estimated by picking the hole edge values that the profile assumes at a depth of 2.5 mm. This parameter is chosen since it is the measure of the hole radius chamfer according to the bar technical drawn provided by VDL Weweler B.V. Then by computing the distance between the two extracted values, the hole diameter is calculated.

Fig. 13 shows four of the N profiles acquired around the hole. The red line indicates the depth of the hole's chamfer radius. The points that intersect the profile (black line) and the red line correspond to the inner edge of the hole and their distance allowed to determine the diameter dimensions. The final hole diameter is estimated by averaging the distances of the N profiles acquired.

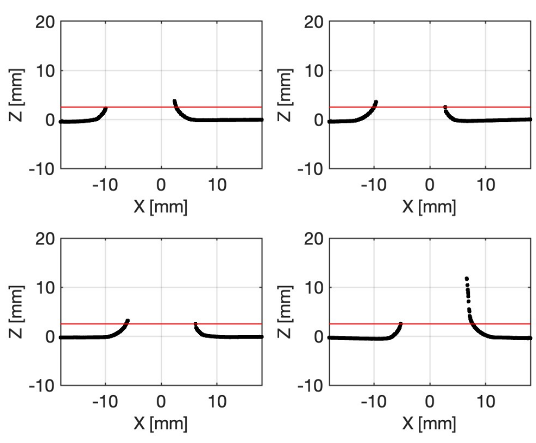

Fig. 13 Hole profiles acquired (4 over N profiles, black dots) and depth line used to measure the diameter (red line)

III. Results

3.1 *Laser line triangulation system for point clouds measurement results*

Fig. 14 and Fig. 15 show different views of the point cloud generated by the match of the four scans performed over the bar. From both figures, the fiducials in the side and frontal parts of the bar are visible.

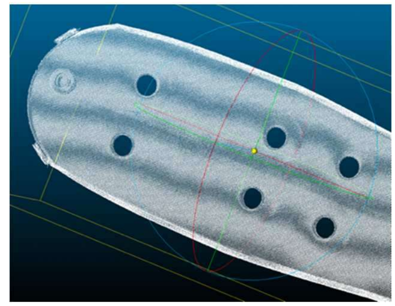

Fig. 14 Point cloud: top view

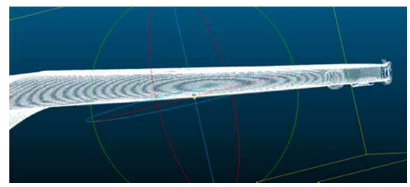

Fig. 15 Point cloud: side view

The match of the 3D point cloud to the corresponding CAD model is illustrated in Fig. 16, it showing a good correspondence.

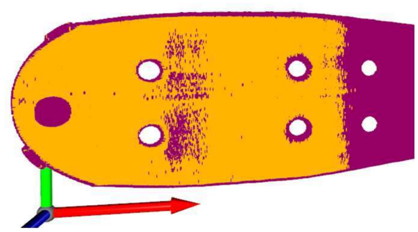

Fig. 16 Match ot 3D point cloud to the CAD model

Fig. 17 illustrates the ROI around one of the hole in the bar. Each profile acquired by the laser line triangulation system is visible. They are used for the point cloud reconstruction.

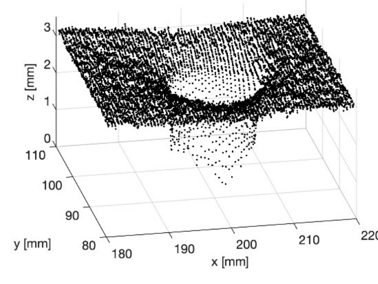

Fig. 17 Profiles acquired near the ROI selected by the laser line triangulation system

From the acquired profiles shown as top view in Fig. 18 it is possible to calculate the hole diameter by performing a circular fit in the x-y plane. The diameter of the hole bar is estimated as 13.35 mm. This value is consistent and respects the tolerance level of ± 0.5 mm defined by the manufacturer.

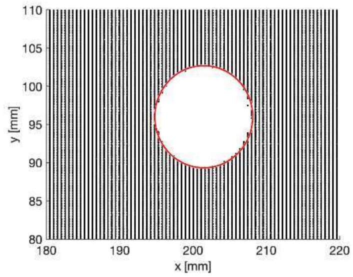

Fig. 18 Circle fit over the hole bar

3.2 Laser line triangulation system 2D features measurement results

Table 1 reports the diameter value extracted from the average of the N profiles acquired around the hole. The hole bar diameter is 12.70 mm with an expanded uncertainty of ± 0.32 mm calculated as twice the standard deviation. This value is consistent and respects the tolerance level of ± 0.5 mm defined by the manufacturer.

Table 1: Mean diameter and standard deviation of the hole

Diameter	12.70 mm
Standard Deviation	0.16 mm

IV. Conclusion and Next Steps

This paper is located within Industry 4.0 and the zero-defect manufacturing (ZDM) paradigm and presents two different robotic inspection systems. The two measurement systems differ mainly in the output they produce.

The first system provides a point cloud, which is characterised by a big amount of data. As a result, extrapolating a single hole bar diameter value requires very time-consuming and off-line post-processing. Future developments, will make it possible to avoid the use of fiducials over the lateral and front side of the bar for point cloud matching. This because the robot movement strategy will be modified. The robot will work either in a stop and go way and its position will be measured or measurements will be taken on the fly if suitable trigger signals can be generated.

The second measurement method, which focuses on the analysis of specific features, can provide an online output of the hole diameter value with much easier data processing. This method makes it possible to satisfy the constraints imposed by the takt time of the production line. The 2D feature extraction method compared to the one which generates the point cloud is also less dependent on the robot's performance. Data acquisition is not dependent from robot velocity and its ability to follow a straight trajectory both along the x-y axis and in the z-x plane. However, in this case the robot position must be known and its alignment with respect to the feature geometry must be set carefully.

By comparing the results obtained, both measurement methods analysed in this study, have produced hole diameter sizes with an uncertainty which meets the requirements.

Acknowledgments

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