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Closed-loop chamfer measurement and control for automated robotic deburring processes

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Abstract
Nowadays, when finishing critical components in the aeronautical sector, inspection of deburring operations is still manually performed outside working stations. This means a great waste of time and prevents the entire work sequence from being executed in an automated and controlled way. Therefore, this work proposes replacing these external equipments with 2D laser scanners, directly coupled to the robot, to verify edge profiles after deburring operations directly at the workstation in a more efficient way. To analyse the feasibility of this technology, a comparison is made between different available measurement laser devices, to determine whether their results can replace those of a reference equipment of the current process. With them, the aim is to streamline and reduce global process time, as well as to establish the next order to be executed by the robot, depending on the measurement result and the tolerance requirements of the workpiece.

Non-contact chamfer measurement; Robotic deburring; Automatic tas assignment; Aero-components

1. Introduction

In the aerospace industry, tight tolerances require high precision for both machining processes and inspection. A particular case of interest would be the finishing of the external connections of the turbine outer-case, where produced chamfer must be contained within very narrow margins (between 0.1 and 0.4 mm). Such components typically have a long history of high value-added operations, subject to very tight dimensional tolerances, where errors result in the loss of a great deal of time and money. However, the variability in the location and size of the burrs hinders the achievement of an acceptable and uniform result after a single operation. Tools available in robotic deburring allow for different material removal depending on their selection and mode of application. However, a complete removal of burrs is not entirely predictable, and isolated areas with material remnants may be present. This usually results in additional deburring operations being required at localised areas to remove excess material, following the strategy in Figure 1.

The problem at present is that this inspection is usually conducted manually outside the working area, driving a profilometer on the negative of the edges obtained by special resins. This means a great waste of time and money, therefore current efforts are focused on automating this type of inspection process with robots. Direct communication with the robot would allow the deburring operations sequence to be controlled according to the measurements results, thus optimising the process to achieve more uniform results in less time. The present study concerns the integration of non-contact technologies for in-process dimensional control of select features of aircraft engine components.

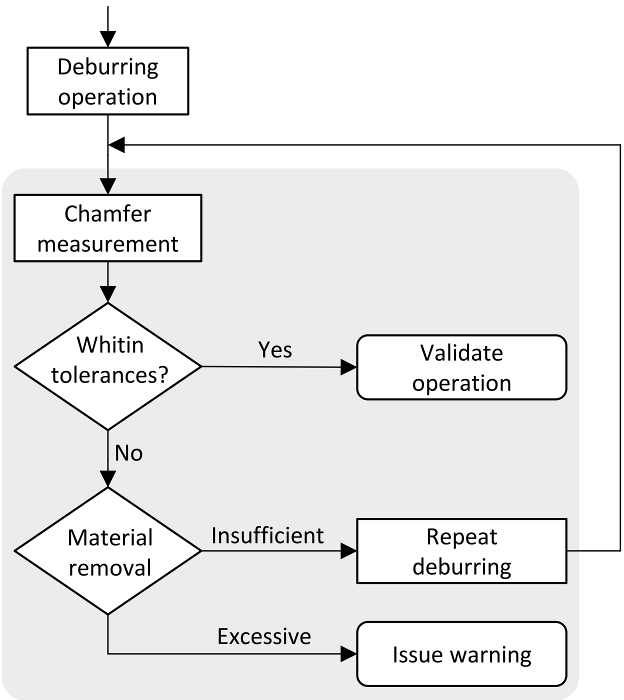

Figure 1. Deburring strategy based on post-process inspection

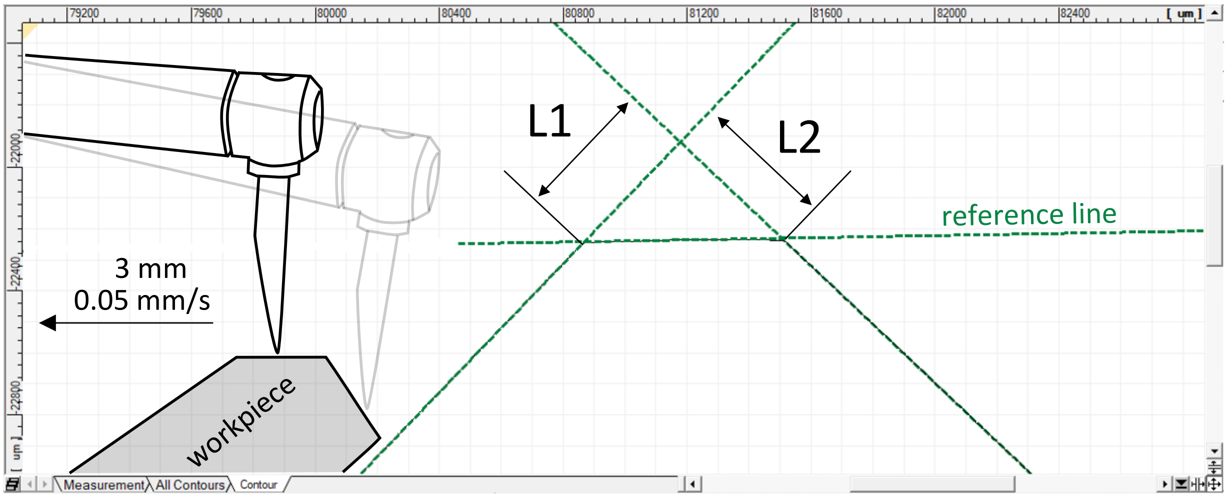

Figure 2. Manual measurement by profilometer

While several commercial alternatives are available for edge measurement control in highly competitive industries [1], the present work introduces closed-loop laser technologies integrated on robotic cells for aircraft manufacturing as a novel approach. In this way, and considering that this technology is also compatible with edge measurement [2-3], this method offers potential advantages over existing technologies and warrants further investigation.

2. Methodology

Comparison between measuring equipment is conducted on 4 uniform chamfers, with sizes ranging from 0.1 to 0.5 mm, on a flat prismatic test part. Three different measurements are made with each device, comparing their average value with the one obtained from a representative instrument of the current industrial context: a profilometer commonly used to accurately inspect this type of profiles.

With the obtained profiles for each chamfer, the standard measurement procedure with this type of parts is based on adjusting and extending contour lines up to the intersection point, which corresponds to the original part edge prior to machining operations. For this 45º chamfer geometry, chamfer size is calculated from the average of the two virtual corners L1 and L2, which are the result of extending upper and lateral sides up to their intersection point. To perform the same procedure automatically, the software used with laser systems allows to identify these auxiliary constructions by means of filters and modifiable setting parameters.

2.1. Reference values obtained with profilometer

The measurement with profilometer is done directly on test part, inclined at 45º to ease access to all surfaces, using a Mitutoyo Formtracer® SV-C3200.

On the one hand, the drive unit (x-axis) boasts an accuracy of ±(0.8+0.01L) µm along its drive length L (mm) for a resolution of 0.05 µm. On the other hand, the detector (z-axis) has an accuracy of ±(1.6+|2H|/100) µm (where H is the measuring height from the horizontal position, in mm) and a corresponding resolution of 0.04 µm. It is equipped with a SPH-71 one-sided cut calibrated stylus, to cover a distance of 3 mm at an acquisition speed of 0.05 mm/s. It is equipped with a SPH-71 one-sided cut calibrated stylus, to cover a distance of 3 mm at an acquisition speed of 0.05 mm/s. Along this path, 2028 points are obtained in total, to be manually processed by the Formtracepak® software included in the equipment.

In this way, test chamfers are referenced to the values from Table 1, a result that is expected to be replicated as far as possible with alternative faster equipment.

Table 1 Chamfers measured with SV-C3200 profilometer

Chamfer	Measured size [mm]	Standard deviation [mm]
1	0.165	$1.225 \cdot 10^{-3}$
2	0.264	$2.357 \cdot 10^{-4}$
3	0.347	$8.165 \cdot 10^{-4}$
4	0.450	$4.714 \cdot 10^{-4}$

2.2 Automated measurement by laser equipment

The laser measurement procedure is analogous to that of the profilometer, but in this case the characteristic points are generated by a laser beam and captured by a camera. Although in some cases the number of points captured may be similar to that of the profilometer (~2000), the larger field of view (FOV) means that they are more widely dispersed, placing a small fraction within the chamfer limits.

However, the main advantage of this technology lies in its immediacy, both in terms of capturing profiles and calculating measurements. To do this, the measurement environment is previously designed based on a representative capture as a test. From this sample, and exploiting the robot's capabilities for the repetition of positioning, each pose is then configured so that it can be repeated over the entire part batch. In these settings, filtering parameters are adjusted to discard those outside the area of interest, thus preventing them from altering the construction of the auxiliary geometries. The dimensions to be measured are defined on the basis of these adjustment lines and the generated intersection points. In addition, it is also possible to set a tolerance margin and thus generate a different command for the robot, depending on each result, in line with the methodology outlined in Figure 1.

Today, there are many different options on the market or laser profile measurement, with different FOV and point capure settings. In this work, the devices listed in Table 2 are compared, ordered from the lowest to the highest point density.

Table 2 Analysed laser measurement devices

Provider	Measured points	FOV [mm]
1	1920	72.5
2	2100	60
3	2048	25
4	1280	10

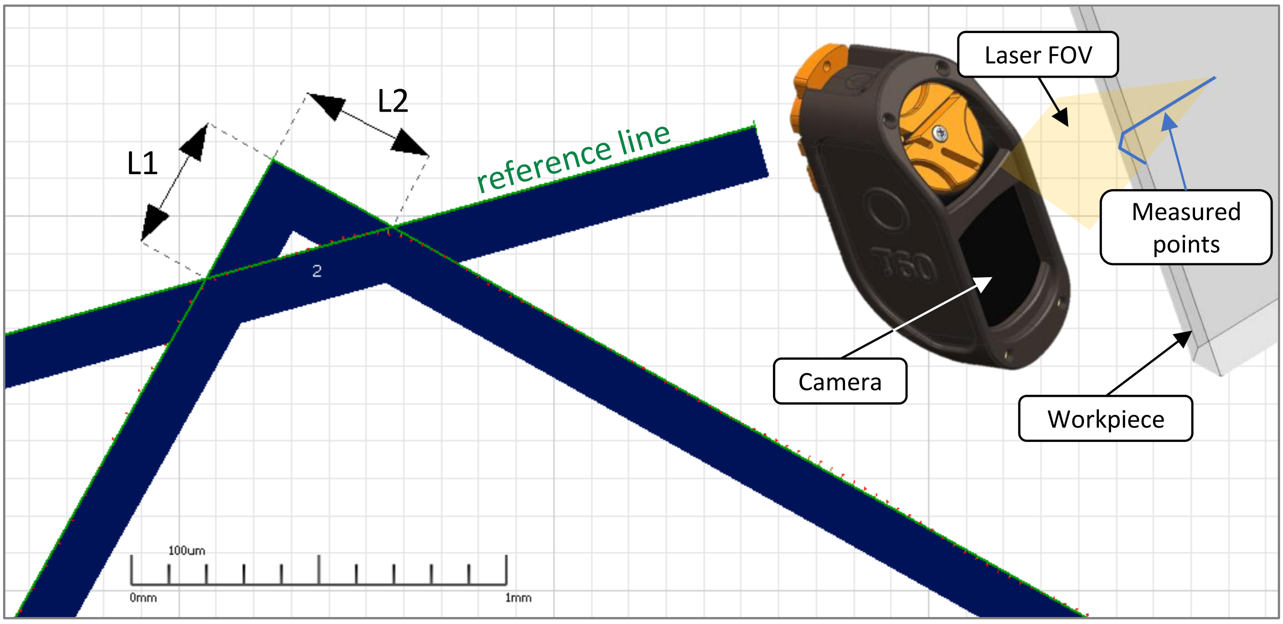

Figure 3. Example of measurement by laser scanner (Provider N.2)

3. Results

The resulting measurements are compared with the ones obtained with the reference equipment. Figure 4 shows the mean deviations obtained for the set of chamfers, with respect to the reference values. Here, it can be seen how the point density greatly affects the measurement accuracy, obtaining better results as this value increases.

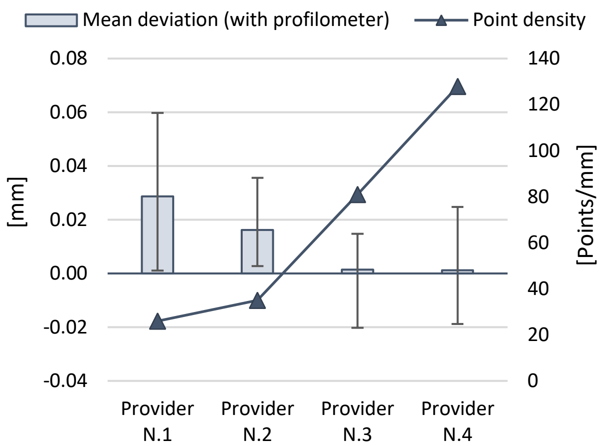

Figure 4. Average deviations in chamfer size obtained with different laser measuring equipment (compared to the profilometer reference value)

In such small chamfers, the number of points captured within chamfer limits is key, as it helps to a better adjustment of the auxiliary lines. In the case of the compared tools, between the best and the worst there is a x6-fold increase in the number of captured points, which is equivalent to going from 3 to 18 points when fitting the chamfered edge at the lower tolerance limit.

Figure 5 plots this deviation as a percentage with respect to the measured chamfer size. Accordingly, it can be seen that only instruments with densities above 80 points/mm are able to measure accurately under all conditions, with percentage deviations below 10%.

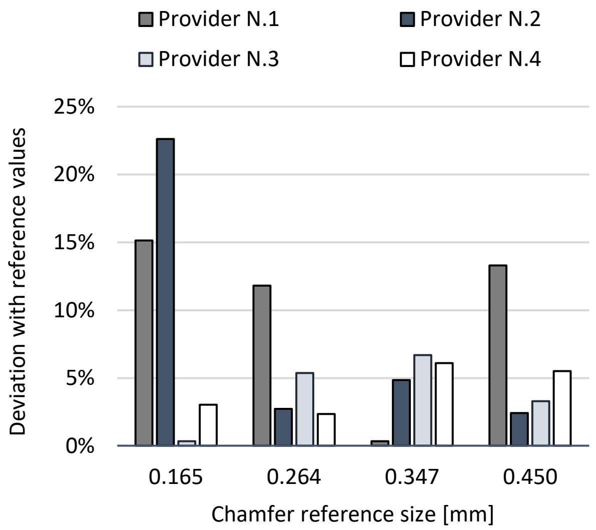

Figure 5. Percentage deviation of the measurements obtained with different laser scanners, depending on the chamfer size.

In the case of the provider N.2, it gives acceptable results for chamfers above 0.2mm, below this level the measurement accuracy worsens considerably. A possible further explanation for this may lie in the positioning error with the robot, which does not measure the geometry in its true magnitude. The more perpendicular the orientation of the beam is to the chamfer direction, the larger values will be with respect to the actual size of the chamfer. This phenomenon is common to all 2D scanners, and should be minimised as much as possible to avoid excessive influence on the measurement result. It can also be corrected by using 3D scanners [5] that align the geometry by processing the point cloud.

If all the measurements obtained with this laser scanner are disaggregated, Figure 6 shows how all the results exceed the reference values obtained with the profilometer.

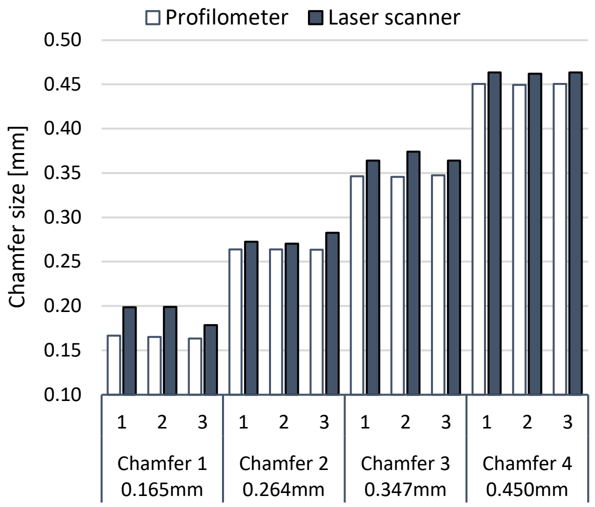

Figure 6. Breakdown of chamfer sizes measured with laser scanner N.2 and SV-C3200 profilometer

4. Conclusions

In this work, different 2D laser profile measurement equipment has been tested, showing how it is possible to achieve results very similar to those of a contact profilometer, when scanners with enough point capture are used, obtaining deviations of less than 10%.

To verify chamfers up to 0.1mm, based on the results obtained, a point density of more than approximately 80 points/mm is recommended.

A critical aspect to control when using this type of 2D scanner is its orientation with respect to the workpiece. In automated industrial environments, the robot is in charge of moving the scanner based on the part positioning, previously generated with other probing or vision methods.

By automating this last link of the manufacturing chain, it is expected that the entire process can be executed in the same way, thus saving time and costs.

Acknowledgements

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