Deliverable D4.1: Validation Report.

Automated robotic system for laser deburring of complex 3D shape parts

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1 Publishable Summary

The automated deburring process of parts with complex geometries usually presents many challenges. To carry out, autonomously, the deburring process operation, 2D and 3D machine vision techniques have been used for different purposes. These machine vision algorithms combined with an industrial robot and a laser cutting head, make possible the full automation of the deburring process.

This deliverable describes the results of the activities carried out on Task 4. This task is in charge of validation of developments and experimentation. More specifically, it reports the validation of the 3D system and the laser deburring process.

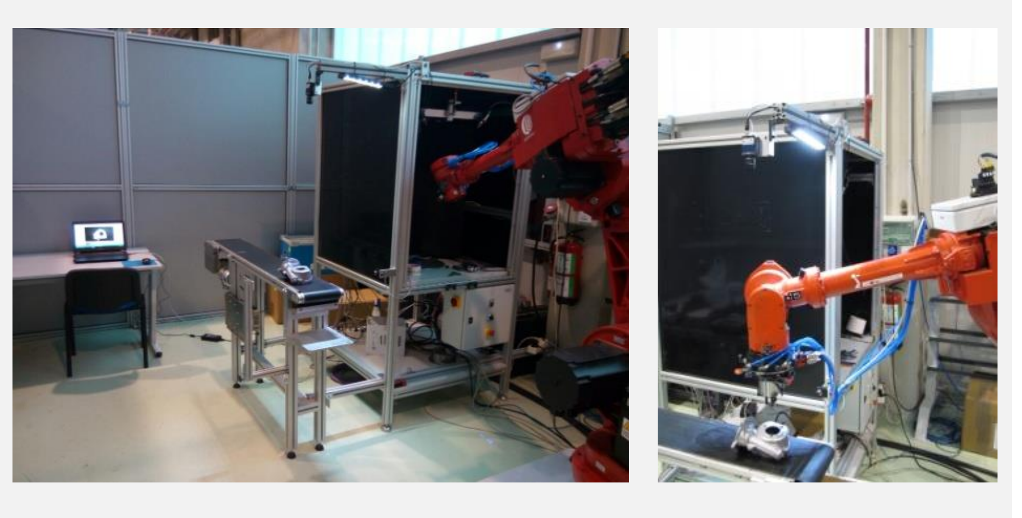
2 3D measurement system performance validation

2.1 Introduction

As explained in previous deliverables, a 2D grasping station and a 3D measurement system have been established in the DEBUR experiment among other developments.

A 2D camera uses shape recognition for part grasping and a 3D vision system is in charge of performing the geometric measurements and burr detection. In addition, the 3D system has the objective of measuring the differences produced when grasping the part at the conveyor, when compared to a benchmark reference. These differences, sent to the robot, allow it to correct its trajectory and therefore, to maintain the accuracy of the cell.

This schema was proposed to give flexibility to the industrial process, allowing manipulation of parts without the need to fix them by special clamping and tooling system, while maintaining the required robot accuracy for laser processing.



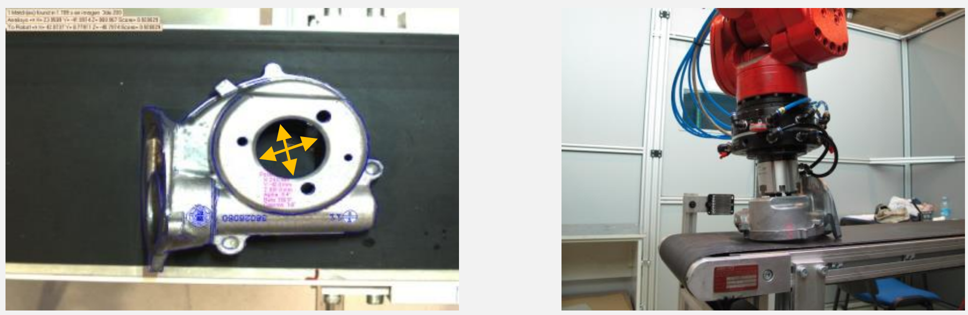
Global view of the cell (left). Detailed view of the vision stations (right).

In the framework of Task 4, we have validated the approach of flexible grasping, by picking the part as it comes from the conveyor, taking advantage of the 3D vision system responsible for measuring the differences on the grasping stage. These deviations are sent to the robot and corrected, so that the part can be moved exactly along the defined trajectory. In further sections of this document, we demonstrate how this method provides a good enough correction, so that the tolerances needed for a successful laser deburring are met in principle.

To validate this approach, part1, an engine bracket, was selected. As a reminder, it is shown in the following pictures, alongside the gripper and fingers used to grasp it.

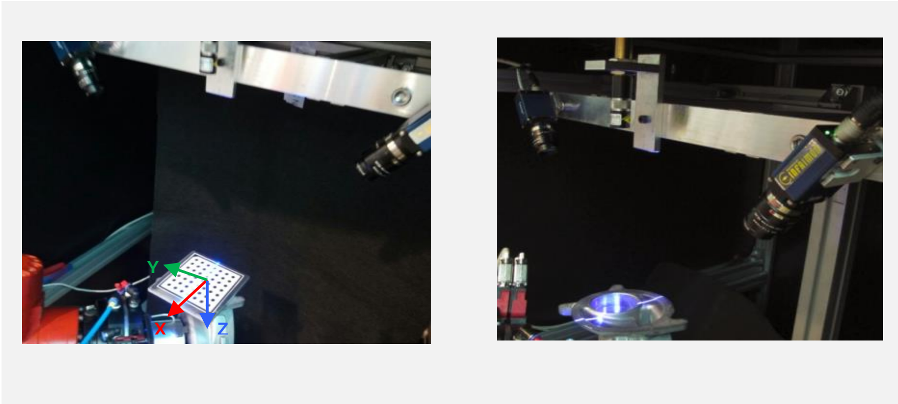
Part showing the grasping point and the gripper used.

In order to validate the grasping step, the part was fed into the conveyor belt with different orientations, so as to test the system in a more demanding way. The following images illustrate how the part is grasped at the conveyor by pose estimation, using Shape-Based 3D matching of a 2D image extracted from the CAD file of the part.



Part analysis before grasping.

Once grasped, the part is measured at the 3D station. This 3D system is shown in the following images. The calibration plate (shown below in the left picture with the virtual reference frame) is used to calibrate and reference the 3D camera and also the robot local frame.



3D station: reference system and validation testing

The validation procedure comprises a two-step sequence. First, a reference position is recorded, by scanning the part with the 3D system. This defines a “benchmark position”. Then, for the next parts, the deviations introduced by grasping are evaluated and recorded. In the second step, the robot moves to the programmed positions, and applies the received correction values from the 3D measurement system. This guarantees that all the parts are located at the same position, within a certain tolerances, before moving to the laser processing stage.

In order to evaluate the accuracy of the method, a line profile based approach has been employed, taking advantage of the same camera set-up used for the 3D system. By recording and analyzing line profiles at two predefined positions, we have been able to calculate the accuracy of positioning in all three-space coordinates, and to do so in a relatively fast manner. Further details are given in the next sections.

Therefore the 3D module of the station has two functionalities: it is used to measure the part and also to control the differences on the positioning of the part at the gripper, due to the flexible way the part is grasped. These deviations have to be tightly controlled, since the laser deburring tool has to be positioned with high accuracy (~0.5-0.7mm).

2.2 Repeatability of the measurement

We have used the 3D measurement system to check the repeatability of the workstation. The measurement system is in a fixed position inside the cell. On this scenario, we have repeated the acquisition of the same part passed several times (at least 6) under the measuring system and compared the results. We have used the first measurement as reference and then analyzed the pose difference between the different obtained models. The main results are shown in the following table.

	x (mm)	y (mm)	z (mm)	a (º)	e (º)	r (º)
mean	-0.14	0.02	0.02	0.00	-0.01	0.16
std dev	0.08	0.18	0.01	0.00	0.00	0.17

These results demonstrate that the 3D acquisition system and robot are synchronized and that the measurements have good repeatability.

2.3 Accuracy after correction

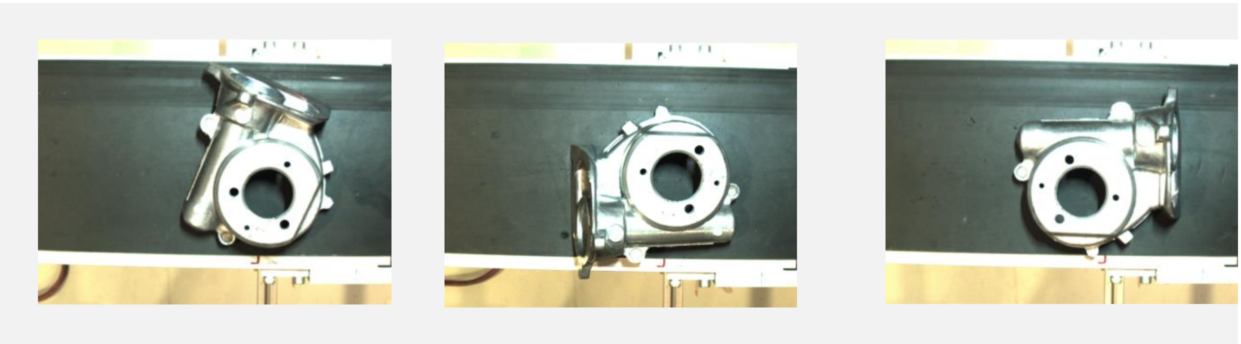
The objective of this validation step is to determine the positioning accuracy of the robot after applying the correction calculated by the measurement system, comparing the actual acquired model against the reference model. With this data as input, the robot repositions. The first steps consist of measuring a part and consider it as the reference. The rest are then measured and repositioned. Then the accuracy is evaluated by image analysis of a line profile.

It is then necessary to check the accuracy in the space coordinates X, Y and Z. To check X and Z positioning, we used the 3D measurement system, by recording a profile image obtained by the camera at a reference point. To check the Y positioning we did not use the installed cameras, due to a limitation in the system set-up. Instead, we used the image acquired by an external camera.

For validation, we use the valid measurement area of the image used in the 3D workstation, which in pixels corresponds to 460 x 1096. In order to obtain information in millimeters, the relation pixel per mm had to be established first. For the estimation of vertical, or Z scale, we moved the robot on the Z direction on the measurement range and kept track of the height coordinate in the robot panel and pixel information on the image. This results in a 0.269 mm/pixel vertical resolution. For the estimation of horizontal X resolution of the camera, we measured the laser sheet of light in mm with a caliper, and the size of the profile on the image in pixel units. This results in a 0.144 mm/pixel horizontal resolution. For Y validation, we use an external camera of 1280x1024-pixel detector size. By measuring in pixels a certain width and comparing it with the real length given by a ruler, we get a relation of 0.219mm/pixel. These factors are then applied to all the calculations. For our validation purposes, these estimations are precise enough.

2.3.1 Grasping

As mentioned before, in order to test the grasping flexibility, we have tested different positions as it comes on the conveyor. The following examples illustrate some of the cases.



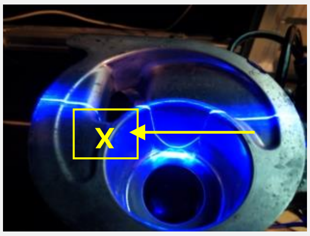
Grasping part in different ways

The validation was done by grasping the same part seven times. Apart from the normal slight variations that the part may suffer during its travel on the conveyor, we wanted to test the system in a more demanding way. Therefore, we generated two cases with a higher degree of difficulty, by rotating by hand the part on the gripper before measurement.

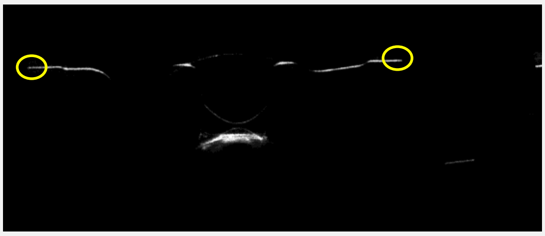
The validation procedure consists in measuring manually, in pixel units, the position of the edges of the profiles under analysis. As mentioned before, the need is to measure the three space coordinates (X, Y, Z), using two types of images (profiles from the 3D system or 2D images coming from the external camera). In order to do so, the robot first grasps the part, which is then measured on the 3D station. After this first measurement has been carried out, the part is then moved again to two predefined positions, where the profiles and 2D image are recorded.

2.3.2 Validation of X positioning

The robot, after the first measurement, is positioned at the corresponding control point, where we trigger the camera to get a profile. We then analyze the recorded image, and extract the location of the limits of the profile. This is shown in the following images:



At position



Analysis on X positioning: measuring points

We repeat this procedure for all the considered parts, in this case seven. Keeping in mind that the detector can be considered a pixel matrix (rows and columns), the obtained values can be expressed as follows:

	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7
Right col	812	813	811	811	810	811	810
Right row	115	114	116	116	116	115	116
Left col	48	49	46	48	48	49	47
Left row	132	129	133	132	132	130	130

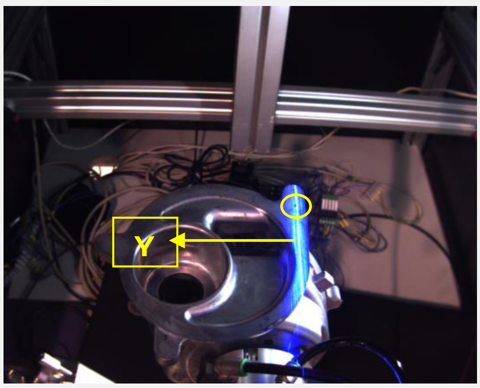
Where the number in the table defines the pixel position at the edges of the profile in the detector matrix. By translating to mm using the aforementioned conversion values, we extract the final results for the X coordinate:

X coordinate	*Ref (mm)*	*Mean (mm)*	*Diff (mm)*	*Stddev (mm)*
Right corner	116.89	116.76	0.12	0.15
Left corner	6.77	6.87	0.10	0.16

The first column reports the selected analysis points, left and right end points of the profile. The second column shows the position measured on the part used as reference. The third shows the mean position of the rest of the parts, while the final column reports the difference in terms of the standard deviation. These results indicate that the positioning of the part is under ±0.5 mm, which is the tolerance required for a successful trajectory execution on the laser deburring station.

2.3.3 Validation of Y positioning

The procedure for validating Y is similar, the only difference being the use of an external camera. The robot, after measurement, is positioned at the control point. At that point, an image is acquired and analyzed. In the case, we fix the column position, so only the row value is recorded.



At position: Analysis on Y positioning

We again repeat the same steps for all the seven tested parts. The obtained values for the pixel location are shown in the next table:

	Part 1	*Part 2*	*Part 3*	*Part 4*	*Part 5*	*Part 6*	*Part 7*
Measured at row 625	822	823	822	825	824	821	823

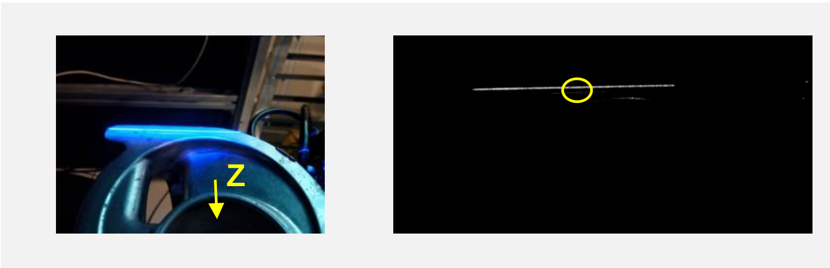
We transform to mm again, with the following results:

Y Coordinate			
Ref (mm)	*Mean (mm)*	*Diff (mm)*	*Stddev (mm)*
180.26	180.45	0.18	0.33

The first column shows the position as measured in the reference part. The second one shows the mean position of the rest of the parts, and, finally, the last columns indicate the difference and the standard deviation. These values are again good enough to maintain the positioning of the part under the ±0.5 mm tolerance required for the trajectory execution in the laser deburring station.

2.3.4 Validation of Z positioning

Finally, for Z coordinate the procedure is again the same. The robot is positioned at control point after measurement. At that point, we trigger the camera to get a profile. This is shown in the following images.



Position Analysis on Z positioning

On the image, we measure the position of the laser profile. We measure the height value at a specific column in the pixel matrix, and keep track of the row value of the pixel of that line. After seven repetitions, the following values are gathered:

	Part 1	*Part 2*	*Part 3*	*Part 4*	*Part 5*	*Part 6*	*Part 7*
Measured at col 470	126	124	127	125	125	123	123

The results in mm are shown on the following table:

Z Coordinate			
Ref (mm)	*Mean (mm)*	*Diff (mm)*	*Stddev (mm)*
33.59	33.50	0.09	0.37

The first column shows the position of the part used as reference. The second shows the mean position of the rest of the parts, in the next one the difference is shown and lastly the standard deviation. We finally can conclude that these values are within the required tolerances for the positioning of the laser head.

3 Validation of laser deburring by roughness measurement and optical microscopy

In order to assess the result of the laser deburring process and to guarantee the quality of the result, two methods have been employed. First, the roughness parameters of the kerf have been evaluated using contact profilometry and confocal microscopy. Then, a broader view of the interaction zone has been obtained by using optical microscopy.

The connecting rod examined in this section has been laser cut using the following parameters:

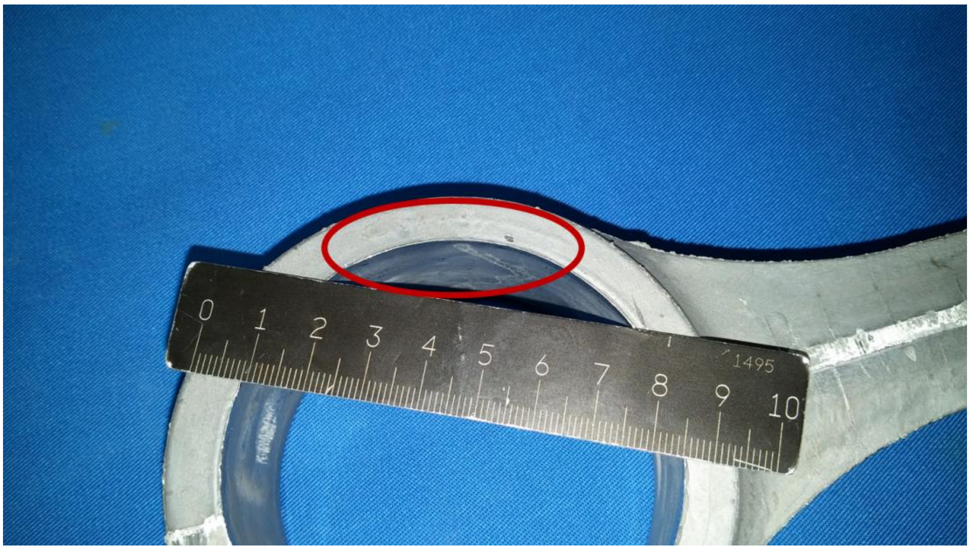
Parameters	Value
Laser power	200 W
Processing speed	100 mm/min
Laser tip diameter	2 mm
Type of gas	Argon
Gas pressure	10 bar
Laser spot diameter	~ 30 µm
Rayleigh length	0.7 mm
Burr thickness	<200 µm

The complete procedure has been documented for the multimedia report, and can be accessed freely at:

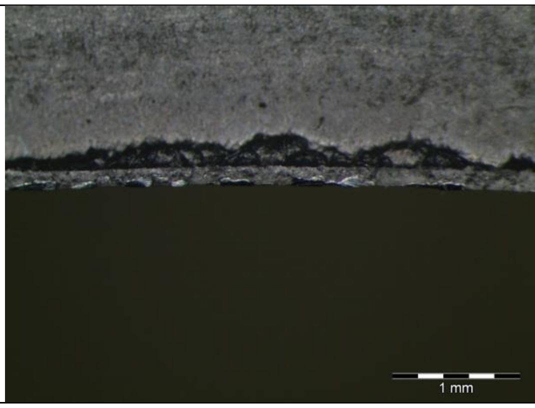
www.youtube.comwatchv=2KqTBzxh7kU

Due to the complex trajectory of the cut and part geometry, it has not been possible to measure the roughness values according to standards. This is because the typical roughness testers move the tip in a straight line, and in this case, the curved trajectory makes it impossible to cover the distance as stated in the standard. Therefore, we have opted for evaluating shorter distances. In any case, the results are meaningful as long as the same parameters are used for all evaluations.

The following picture presents an overview of the overall result. The treated area is highlighted in red colour.



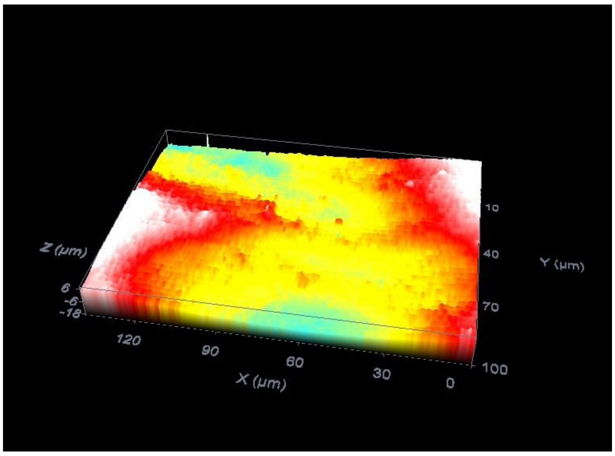
A magnification lens has been used to check the details around the cut. As shown in the next pictures, the kerf zone has good quality, with no burrs, dross or recast material attached to the part.



The roughness parameters have been measured also in the zone shown in the previous pictures. The evaluation distance has been of 0.25 mm, using 3 evaluation lengths and a standard Gaussian filter. The values for the R parameter family are:

Parameter	**Value (µm)**
R_a	1.21
R_q	3.83
R_z	1.38

Then the sample has been examined using confocal microscopy, in order to obtain topography information in a wider area. A 100x objective has been used, which provides a field of approximately 140 x 105 μm^2 and a spatial sampling resolution of 0.18 µm.



The higher locations in the topography correspond to the points in white, with an approximate height of 10 µm. Average surface area parameter S_a is around 2 µm, which is a bit higher than the corresponding 1D parameter extracted by contact methods.

The results show that the quality of the cut is good enough, far below the values set forth in the requirements document, which stated a Ra roughness of ~1 µm. However, a slight degradation in quality is to be expected in parts with higher burr thickness.

4 Conclusions

- The validation carried out, shows that:
  - The results shows that, after allowing a flexible grasp of the part, the accuracy of the corrected positioning will be good enough so as to keep the robot trajectory within the required tolerances for laser deburring.
  - The results show that the quality of the cut is good enough, very close to the values set forth in the requirements document, which stated a Ra roughness of ~1 µm. However, a slight degradation in quality is to be expected in parts with higher burr thickness.