Deliverable D2.2: Grasping and fine trajectory tracking

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

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1 Publishable Summary

This deliverable describes the results of the activities carried out on tasks 1 & 2. On them the different workstations have been designed and developed and put them together in the deburring cell.

The deburring process of parts with complex geometries usually presents many challenges to be automated. On this document there are explained the machine vision techniques, involved in the design and set up of an automated adaptive cognitive robotic system for the laser deburring of metal casting 3D high quality complex parts, and the laser deburring technology applied on the final demonstrator. To carry out, autonomously, the deburring process operation, 3D machine vision techniques have been used for different purposes. These machine vision algorithms combined with industrial robots and a high tech laser cutting head, make possible the fully automation of the deburring process. This setup could potentially be applied to medium sized parts of different light casting alloys.

On the following pages it is documented the status of the different workstations: the grasping step, the 2D and 3D workstations, and the deburring process workstation. The robot task (programming) has its own section. Finally, the central control of the cell it is documented.

2 Task 2: Design and development of the different modules of the cell.

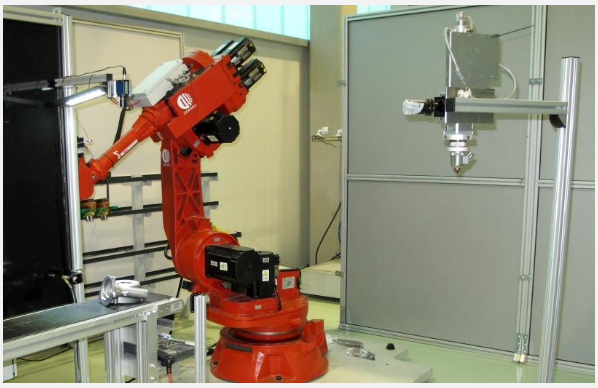
2.1 Description of the cell

The automatic deburring cell consists of the following components:

- Robot and grasping system
- Conveyor belt and 2D pose estimation workstation
- Burr measurement by 3D workstation
- Deburring process workstation
- Output station

All the elements are set together inside a cell within the robot working range distance. This cell operates inside with an enclosure of 2.5 m height. This protects the outside from laser emissions, since the laser head works with a 200 W source, enough dangerous for the staff working on the adjacent shop floor.

The following figures visualize the different elements of the cell. The robot is a COMAU NM-45 with a 45 Kg payload.

	
Global view of the cell	Detail of 3D and 2D stations

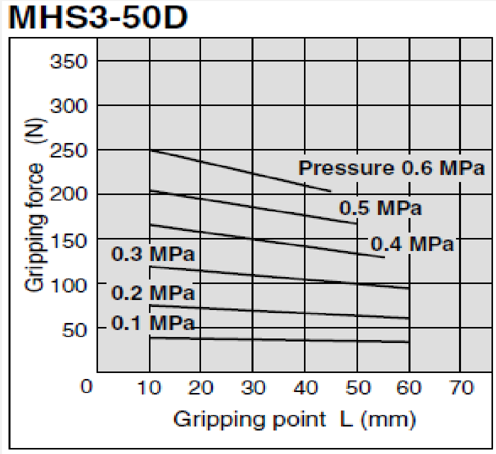
At Debur project, the robot is the actor that will move the part through the different workstations. A conveyor belt introduces the part to the cell. A photoelectric cell stops the part under a 2D camera. This is the 2D workstation, which estimates the pose of the part and passes it to the robot in order to grasp it and introduce it into the cell. With the part grasped, the robot introduces it in the 3D workstation for measurement. After measurement and estimation of size and position of burrs, the part is moved to the deburring workstation where the laser will remove them. In the final step, the robot leaves the part in a table (parts deposition area).

A detailed description of the activities done and the final state on each workstation it is shown below.

2.2 Grasping

Attached to the robot flange, a grasping pneumatic gripper has been designed for the manipulation of the part. The system is valid for diffferent parts, for that, it is enough to change the end effectors of the gripper.

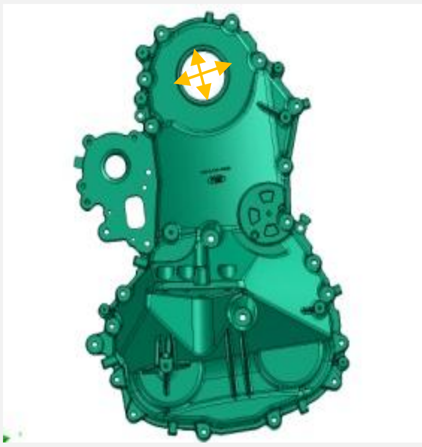
Gripper MHS3-50



Force

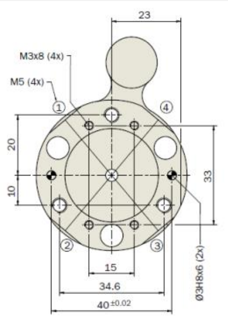
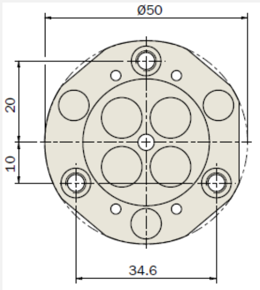
Parts required for manipulation on Debur project have a circular ring. For this reason the gripper has three fingers that may be manufactured depending on the part geometry to be grasped.The design of the gripper fingers has been done and manufactured.

Part 1: gripping area



Part 2: gripping area

For the robot flange it has been designed a manual interchange system. This gives much more flexibility for an efficient use of the cell. It allows the robot to attach the laser head for laser deburring testing or to attach the gripper for grasping testing and burrs detection at 2D and 3D workstations of the cell. Three interchange systems are required: one is fix and goes attached to the robot flange and the other two are for the removable systems. All needed elements, like the materials, the gripper and the interchange systems have been purchased. The mechanical interfaces, required to attach the interchange systems to the robot flange, the gripper and the laser head, have been designed and manufactured.

		
Fixed to the robot	Gimatic system: both sides	One for every each attachable tool

The final set is shown in the following pictures. On them it is shown the grasping of the part in two different ways, depending on how the part arrives on the conveyor.

		
Gripping inside	Grasping the part	Gripping outside

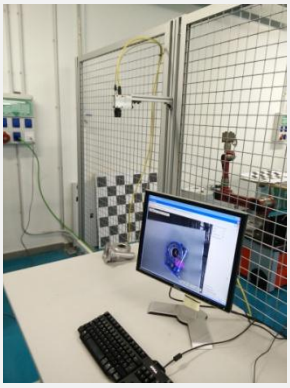
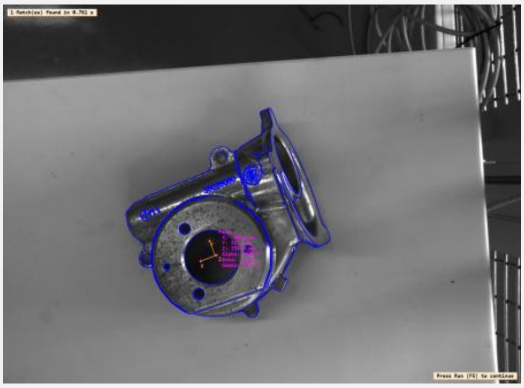
2.3 2D Station

This station includes both the conveyor belt and the analysis camara. In this step, parts arrive to the deburring cell by the conveyor belt. At the end of the conveyor a fotoelectric barrier stops the part under the cameras field of view. The robot commands this conveyor start/stop automatism. The camera image makes a pose estimation of the part for being grasped by the robot, based in a 3D pose estimation using Shape-Based 3D matching.

The 3D pose estimation is based in a matching between the CAD design of the part and the obtained 2D image. For matching, a 3D shape model of a reduced view of the CAD model of the part on it position is constructed. The model is obtained through 2D projections, acquired at different angles close to the target view. The model may be very complex and therefore very time consuming. On Debur project, the parts come on the conveyor at a few allowable positions. The needed models are reduced to those positions, allowing an efficient matching and pose estimation of the part.

2.3.1 2D station prototype.

To make the development and analysis of the 2D station a prototype with the selected camera was installed on the lab at similar situation than at its final destination over the conveyor. After the first tests and trials, it was decided to place the camera in a zenithal position to the conveyor belt, supported on an aluminium profile. The analysis technique used is a 3D pose estimation based in the 2D image matched against a partial view model obtained from the CAD.

		
Camera and image	Pose estimation	2D prototype

The constructed prototype replicates the estimation of the pose of the part on the conveyor. Since the tested part can come in two different ways, they have been extracted two possible models. They are used techniques for shape-based 3D matching using projections of the CAD model of the part in the 2D image of the camera. Each desired model is obtained moving a CAD representation of the part in order to delimit the possible ranges of the part on that position. The camera algorithm is then able to match the part with the model and extracts the pose of it.

An operator function have been used to generate the shape model, taking into account that part type 1 that may arrive to the cell conveyor in two different positions as well as part type 2. It has been parameterized one model for each position. For every grasping position of the part, it has been generated a subCAD model, attending to the relative pose that the part may have respect to the camera. In this way the obtained image is matched against each model. Best match is resolved as a pose position of the part relative to the camera origin. This pose will be used by the robot to grasp the part and introduce it on the cell.

The tests done on the prototype were successful and the parts pose correctly estimated. Next steps on the final cell will require calibrating the camera on its final position over the conveyor, to integrate its coordinates system into the robots world, to integrate the algorithm in the PC control of the cell and to tune the grasp of the part by the robot in order to optimize its position for next workstations.

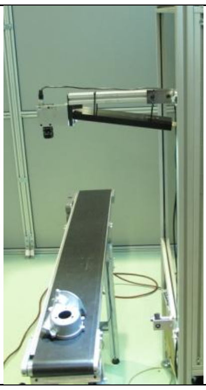
2.3.1 Final installation

The final elements selected after testing in this station are:

- Camera Genie HM1280 1/3” 1280x960 CMOS
- Optics F1.4/16mm

At its final placement it is needed the last precise calibration of the camera.

This procedure comprises integration to robots coordinates.

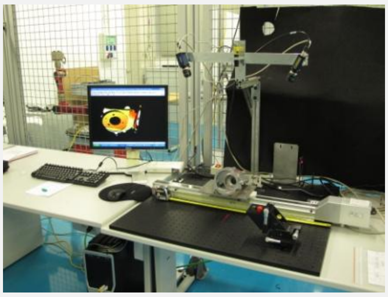
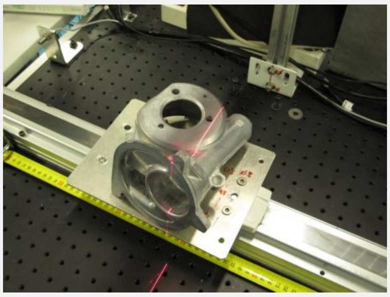
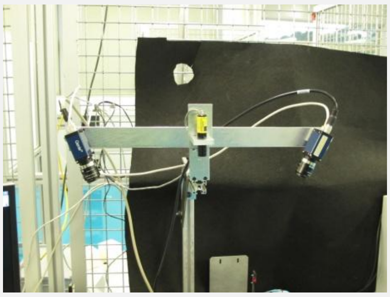


Conveyor belt and 2D station

2.4 3D Station

2.4.1 3D station prototype.

For the 3D workstation it was tested a two camera sheet of light system. This construction reduces occlusions on the acquired model. It was constructed using two commercial area scan cameras due to their competitive price when comparing with integrated sheet of light systems. For the initial analysis it was constructed an auxiliary 3D station using a linear axis, for the movement, that replicates robot movement of the part.

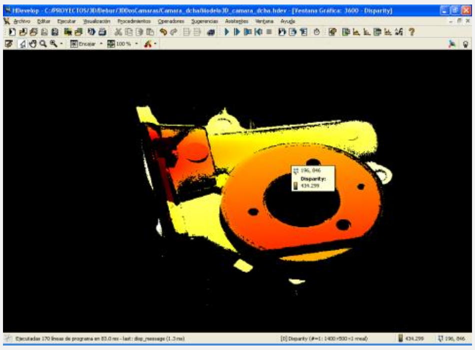
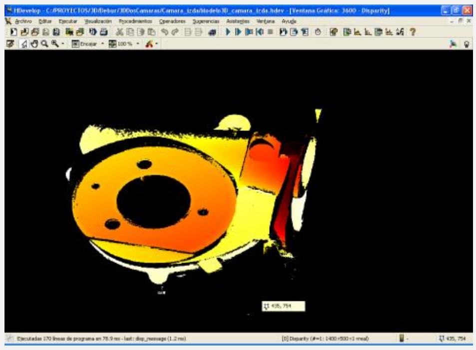
		
Global view	The part moving	Cameras

These images illustrate the constructed prototype. The left image is a global view showing the different elements: the linear axis, cameras, sheet of light and working station for development. The other two pictures shows a detail of the cameras and sheet of light and the moment where the part is being acquired by the vision system for posterior analysis.

The linear axis is configured to generate n pulses per revolution that triggers image acquisition. This prototype allows analyzing different settings before it is integrated on the final cell.

To optimize the capture it was reduced the acquisition image size of the camera. A trick has been performed to maintain the calibration of the camera simultaneously with the ROI size of the sheet of light, that it is constrained to just a part of the total image scene. This procedure speeds up the acquisition time for the sheet of light system. The power of the control system makes the rest and the analysis is done in a very small amount of time. It allows preparing the deburring work-station before the part reaches it.

After the acquisition by both cameras two 3D model of the part are obtained as it is shown in the following figures.

	
Left camera: 3D reconstruction	Right camera: 3D reconstruction

These two independent models have to be integrated into one to reduce the occlusions generated at each model. For the analysis of burrs, in the 3D workstation, the three principal steps were:

- 3D reconstruction of the part, using sheet of light techniques and registration methods in order to obtain a point cloud volume avoiding shadows and occlusions.
- Point cloud filtering and clustering to obtain a robust model of the part under inspection.
- Matching with the part CAD model, STL file in this case, to obtain volume differences corresponding to burrs.

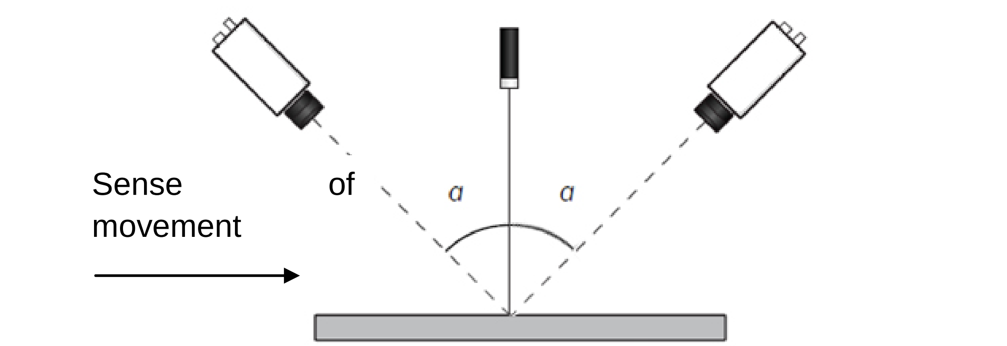
The following subsections explain more in depth the different steps.

2.4.2 3D reconstruction and partial view registration

The sheet of light setup used for 3D reconstruction is a dual camera system, in a reversed ordinary setup configuration. The reversed ordinary setup provides a good height resolution avoiding miss-register problems. The height resolution obtained with this setup can be expressed as follows:

$$\Delta z \approx \frac{\Delta x}{\sin(\alpha)} \qquad (1)$$

The dual camera system is mounted in the sense of the relative movement of the part under inspection, so occlusions due to geometry are avoided. This setup can be seen in the next figure. Additionally, for each cameras calibration has been performed so that the partial point clouds are obtained directly in real world coordinates, in this case, mm, which are the units in the part STL model.

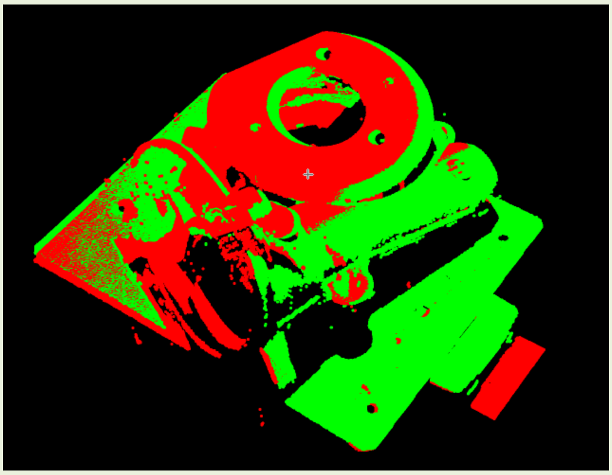


Schematics of the dual camera laser triangulation system, in reversed ordinary setup.

For the registration of both partial reconstructions obtained from the part, key points have been extracted using the scale-invariant feature transform algorithm. Having obtained the key points, the registration is performed in two steps, first using FANN algorithm for initial registration of clouds, and ICP in a second step to minimize errors, obtaining as a result the affine transformation of the point cloud of the second camera with respect to the other, taking as coordinate reference the first camera in the sense of movement:

$$H_{registration} = H_{icp} H_{fann} = \begin{bmatrix} R_{icp} \cdot R_{fann} & R_{icp} \cdot t_{fann} + t_{icp} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix} \quad (2)$$

Transforming the second partial point cloud by Eq. 2 and adding the points to the first point cloud taken as reference, a first registration step is achieved. This initial step can be seen in the next figure:



Registration of the two partial point clouds (red and green) obtained.

2.4.3 Point cloud preprocessing

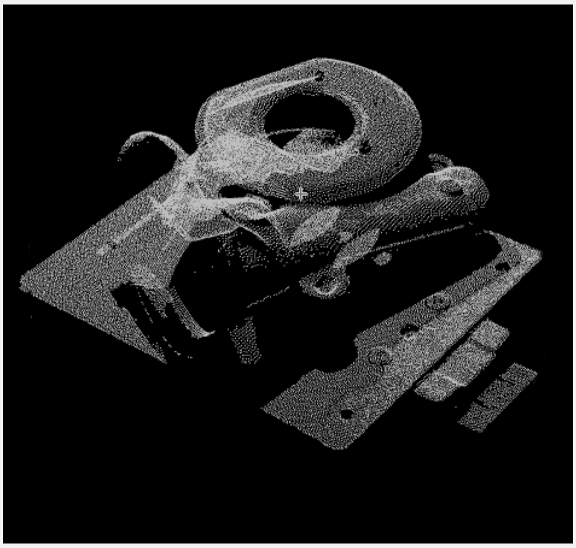
After obtaining the registered point cloud, further processing is needed to obtain a suitable 3D volume to be compared against the STL model of the ideal part. All needed configuration parameters in the different operations have been fixed empirically after performing some tests, and taking into account the characteristics of the initial point clouds in terms of number of points and spatial resolution in X and Y axis. Operations applied on the point cloud with brief description and parameters are listed below in order of application:

- Outlier removal: Using the euclidean distance as measuring criterium, an outlier in the point cloud is defined as a point whose mean distance to the k nearest neighbours is bigger than D mm, with k = 3 and D=5.
- Downsampling using a voxel grid filter: All the points within voxel cubes of edge d millimeters, are substituted by a new point, the cube centroid. Voxel cubes containing less than n points are removed from the point cloud. d = 0.5 mm, n = 5 points.
- Smoothing of the downsampled point cloud. For point cloud smoothing MLS algorithm is used. MLS smoothing algorithm fits a planar surface or a higher order polynomial surface to its k nearest points. The surface fitting is a standard weighted least squares parameter estimation of the plane or polynomial surface parameters, respectively. The closest neighbours of P have higher contribution than the other points, which is controlled by the following weighting function with a parameter φ:

$$w\left(P^*\right) = e^{\left(-\frac{\left\|P^* - P\right\|^2}{\varphi^2}\right)} \qquad (3)$$

The point being processed is then projected to the calculated local surface, with a relative φ = 1.0.

Applying these three steps to the initial registration process explained, a smoothed model with less noise is obtained, suitable to be used for detecting burrs in the part, comparing it with the initial CAD model. Next figure shows the final model of the part reconstructed.



Final model after outlier removal, downsampling and smoothing.

2.4.4 Matching with CAD model and burr detection

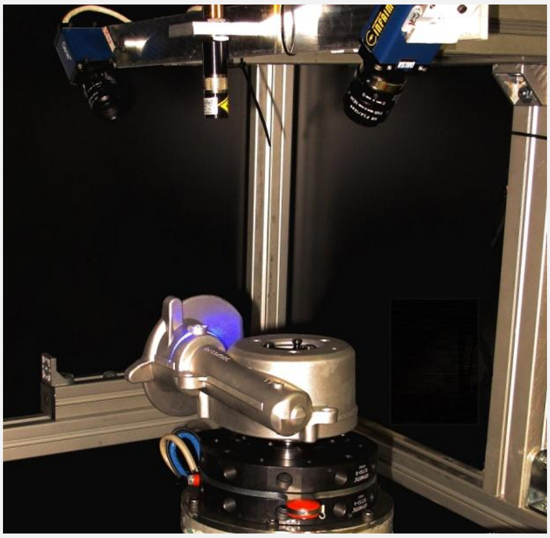
For burrs detection, the point cloud model generated in the previous section is used to carry out a registration with the STL model. The registration operation is based essentially in the same procedure explained, taking as point clouds to register the generated 3D model from the scanned part, and the STL design model available. Once the complete registration is performed, distance from the scanned part to nearest model surface is calculated, by establishing a threshold in distance, points whose distance is over that threshold are marked as burr points.

The last step is a 3D clustering of these points, to obtain position and size of the burr to be removed by the laser.

2.4.5 Final installation

The elements used in this station are:

- Two Camera Genie HM1400 monochrome 1400x1280 CMOS
- Optics F1.4/16mm
- Laser line generator: Z-Laser Z030M18H-F450LP30 (blue, 30mw, 450 nm and with a LP30 optic)
- Band pass filters: IBP470 centered at 470 nm



3D final setup

On the final workstation integration of the 3D system, the image acquisition will be done by firing only one trigger pulse: the start. The acquisition will be a number of frames obtained over the lineal movement of the robot at constant speed. This procedure may look less precise than an encoder triggered acquisition, but it is considered that the part will be moved under the cameras by the robot. An encoder acquisition approach on the robot requires to convert, in a parallel task, actual positions into pulses checking actual position against a desired increment of displacement. The exact determination of the increment may be imprecise or slow. Instead, the frame rate is considered constant frequency in the camera acquisition system since no analysis will be included during the robot movement. The movement of the robot can be precisely considered as totally linear. It will be needed a procedure to coordinate images frame rates with robot speed to correlate movement with real dimensions.

2.5 Laser deburring process

Monitoring activities

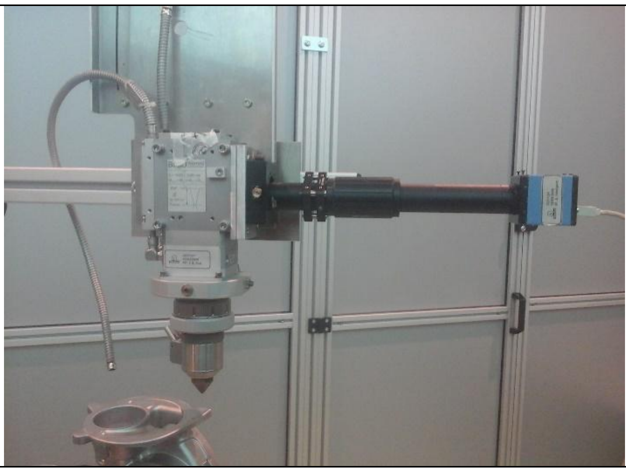
Regarding the activities carried out to monitor the laser process, two strategies have been designed: imaging the process and spectral monitoring of the physical processes. In the first case, the idea is not only to visualize the process but to obtain different 2D information about the zone close to the laser beam. For this, a coaxial arrangement for the camera by means of a dichroic mirror has been designed. This allows inspecting the process using the optical path of the laser. The requisites for the design were on the one hand to design an optical system able to change the magnification from 0.5 to 2. On the other hand it was also important to have the ability to insert spectral filters in order to record only the relevant information of the process. In fact, there are several physical processes that emit light in different spectral regions (plasma, thermal radiation, laser beam scattering, etc.) and it is necessary to focus on just one of these phenomena to extract the suitable information for process controlling purposes. In order to build a coaxial imaging system by means of a dichroic mirror, one has to take into account that the magnification can be calculated with the following rule:

$$M = \frac{f_{tube\ lens}}{f_{objective}}$$

The focal length of the objective is 150 mm, so this drives us to use lenses with focal lengths in the range 75-300 mm to obtain a magnification from 0.5 to 2 respectively. The field of view of the camera will be modified accordantly to the following expression:

$$Field\ of\ view = \frac{size\ camera\ sensor}{M}$$

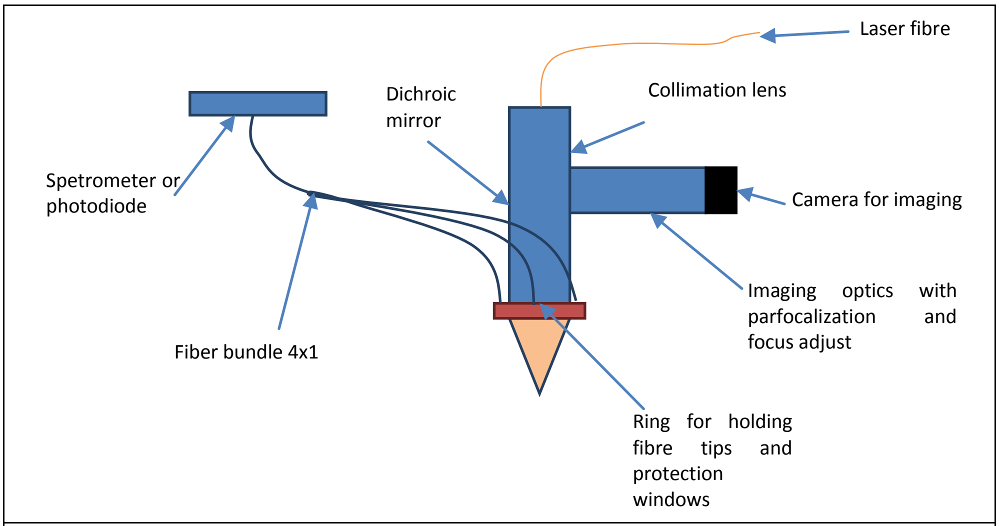
Taken this into account, we have built a flexible optical system that allow us to use different type of cameras and tube lenses in order to explore a wide spectrum of configurations for recording 2D images of the process with different characteristics (variable magnification, spectral and time resolved imaging, etc.). The elements for the imaging optical system have been provided by Thorlabs. In the following picture it is shown the optical system with a camera. The system is long because of the 300 mm focal length of the lens for the maximum magnification.



Monitoring optical system

A deflection mirror has not been contemplated at first instance. So the number of optical elements is maintained at minimum and no additional restriction in the spectral range due to the use of a reflection coating for the mirror is introduced.

For the pure spectral analysis of the process by mean of spectrometer and photodiodes the use of a coaxial approach is not the most suitable technique. In fact the spectral transmission of the focussing lens in the nozzle and the spectral dependence of the reflection coating in each dichroic mirror would affect the results and should be taken into account when analysing the data. Therefore, a different strategy has been considered and a direct view of the process for these elements will be implemented. In the literature one can find several scientific articles describing experimental setups in which one or more sensors (mostly photodiodes with, in same cases, additional features to focus on specific parts of the spectral range) are placed close to the process. In our case, we will use one sensor (either a photodiode or spectrometer) together with a fibre bundle to measure at different points. The following picture illustrates this idea:



Monitoring setup

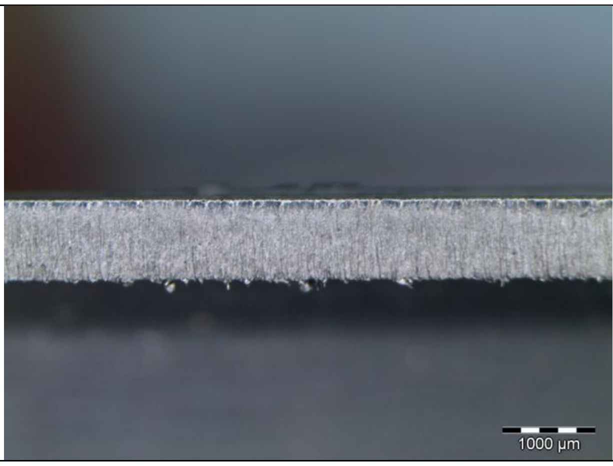
Hence, the experimental setup described here should allow us to measure most of the relevant characteristics of the laser process and thereby using the data for extracting information that can be used to implement a strategy for the control of the process.

Processing activities

In addition, a preliminary laser deburring tests have been performed varying the most important process parameters (laser power, processing speed and gas pressure) in order to obtain a proper set of parameters. Best results have been achieved using the parameters exposed in the following table.

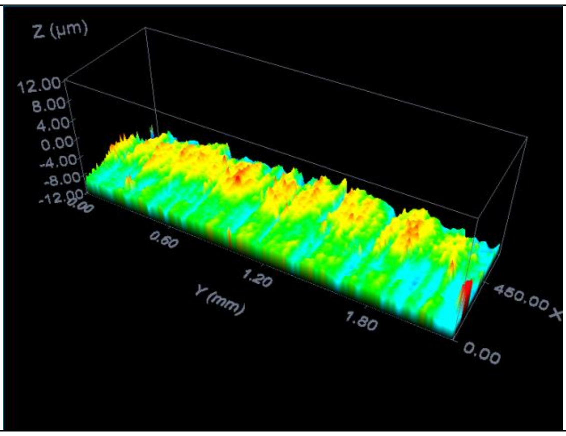
Parameters	**Value**
Laser power	200 W
Processing speed	100 mm/min
Laser tip diameter	2 mm
Type of gas	Ar
Gas pressure	10 bar
Laser spot diameter	~ 30 µm
Rayleigh length	0.7 mm

The following image shows the resulted profile of a 1 mm thick cast aluminium burr after the cutting process.

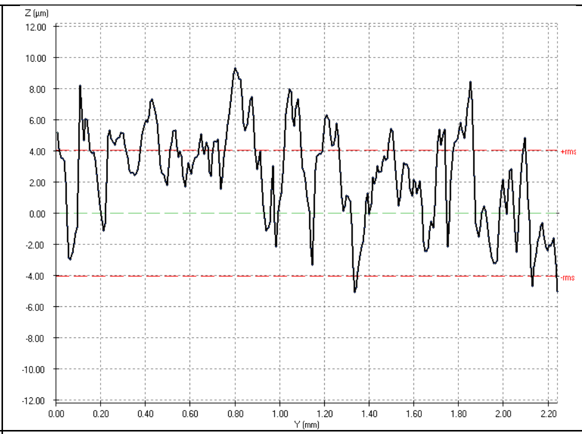


Profile of the removed burr

In the image of the removed burr cross section it can be seen a ribbed profile and small burrs, however finishing quality is quite good, as it is shown in the topography and cutting profile, obtained by a confocal microscope, of the following figure. The roughness achieved, measured in Ra, ranges between 2.5 µm and 3.0 µm.



Topography



burr profile

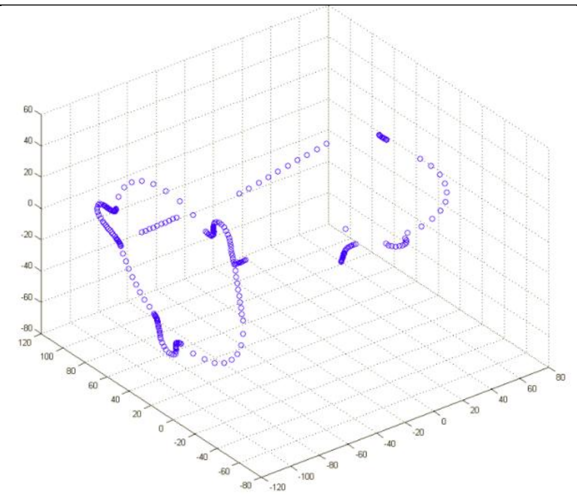
2.6 Robot path

Generally, in aluminium casting alloys, the areas where burrs are to be treated usually appear along the closure line of the mould. On the Deliverable D 2.1 there were some images showing where the burrs may appear at part type 1.

Burs area 1

Burs area 2

On the CAD, the areas of the part where burrs may appear are defined. The deburring trajectory of the robot is defined using the CAD.



Robot path from CAD: burrs area

	x	y	z	descriptor
Point 1	-100.33	-24.76	40.65	d1
Point 2	-100.72	-24.33	42.85	d2
Point 3	-101.07	-23.21	44.80	d3
Point 4	-101.33	-21.51	46.30	d4
Point 5	-101.48	-19.41	47.17	d5
Point 6	-101.51	-17.14	47.34	d6
Point 7	-101.41	-14.94	46.78	d7
Point 8	-101.20	-13.03	45.55	d8
Point 9	-100.89	-11.63	43.78	d9
Point 10	-100.51	-10.87	41.67	d10
Point 11	-97.19	-25.42	22.80	d11
Point 12	-97.54	-25.35	24.78	d12
Point 13	-97.89	-25.27	26.77	d13
Point 14	-98.23	-25.20	28.75	d14
Point 15	-98.58	-25.13	30.73	d15
Point 16	-98.93	-25.05	32.72	d16
Point 17	-99.28	-24.98	34.70	d17
Point 18	-99.63	-24.91	36.68	d18
Point 19	-99.98	-24.84	38.67	d19
Point 20	-100.33	-24.76	40.65	d20
Point 21	-90.36	-24.39	-15.93	d21
Point 22	-91.11	-24.50	-11.63	d22
Point 23	-91.87	-24.62	-7.33	d23
Point 24	-92.63	-24.73	-3.02	d24

Robot path points definition plus descriptor

On the 3D station the 3D point clouds obtained will be used to measure the burrs in these specific regions. The analysis will give as result the size and position of burrs. The robot trajectory generated by the CAD will be completed with descriptors accessible from the central unit of the cell. Then, the information coming as result of the 3D analysis of burrs will modify robot behaviour, in the form of start/stop instructions and trajectory optimization through these externally modified values.

Every CAD point is transformed to a robot instruction in the form:

MoveL Offs(p_initial, ***δ*x, *δ*y, *δ*z**), **v_d1**, z5, t_debur \WObj:=wobj_laser;

Every robot movement is commanded defining the offset from the initial point δx, δy, δz. The 3D station defines the command speed to be applied v_d1 that is determined on the 3D measurement workstation.

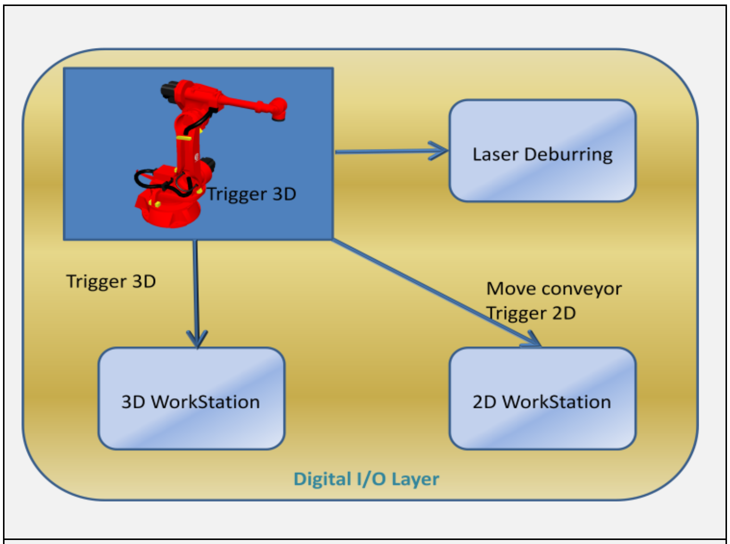
This way, the result of the 3D analysis will be parameterized and integrated in the robot trajectory. The value of this parameter/descriptor will serve to control the speed of the TCP of the tool. When this parameter is high due to the detection of high size burs will command lower speed and when this parameter is low due to the absence or detection of small size burs will serve to command higher speed.

The generation of the robots trajectory will be automatically generated at the 3D workstation rewriting the CAD points to robot movement instructions.

2.7 Central control of the cell

The integration of the different systems of the cell is done in two layers.

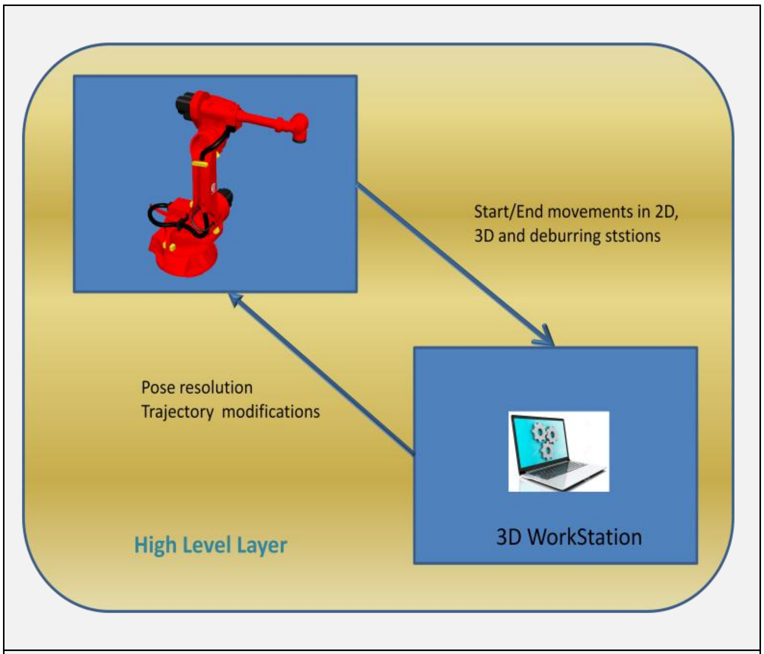
The first layer is responsible for low level communication layer. It is based on the digital I/O of the robot. This layer is governed by the robot and controls the movement of the conveyor, the triggering of the 2D cameras, the triggering of the 3D system and the interface with the laser system.



The physical communications layer

The second layer is a high level communication layer that uses TCP/IP Ethernet protocol for communication. A portable PC with high specifications: graph capacity and fast processing characteristics to handle the two 3D cameras, the point cloud analysis is at the same time in charge of the control of the cell.

Over this layer, the laptop communicates to the robot, the pose of the part to be grasped and analyze the 3D real model of the part. Extract the burrs and sends to robot the trajectory corrections based in their position and size.



The ethernet communication layer

3 Conclusions

- The deburring cell has been designed and constructed and is ready to operate with:
  - The conveyor belt ready.
  - The 2D station ready.
  - The 3D station ready.
  - The robot with a manual tool change possibility for laser operations, grasping and 3D analysis tuning ready.
  - On-line monitoring deburring process.