PROJECT DELIVERABLE REPORT

Project Title:
Zero-defect manufacturing strategies towards on-line production management for European FACTORies

FOF-03-2016 - Zero-defect strategies at system level for multi-stage manufacturing in production lines

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### Abbreviations for the Consortium

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<tr>
<td>CERTH</td>
<td>ETHNIKO KENTRO EREVNAS KAI TECHNOLOGIKIS ANAPTYXIS</td>
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<td>HOLONIX</td>
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<td>DATAPIXEL SL</td>
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<td>INOVA+</td>
<td>INOVAMAS - SERVICOS DE CONSULTADORIA EM INOVACAO TECNOLOGICA S.A.</td>
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<td>SIR</td>
<td>SIR SPA - SOLUZIONI INDUSTRIALI ROBOTIZZATE</td>
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<td>DURIT</td>
<td>DURIT METALURGIA PORTUGUESA DO TUNGSTENIO LDA</td>
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<th>Acronym</th>
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<td>BOM</td>
<td>Bill of Materials</td>
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<td>CA</td>
<td>Consortium Agreement</td>
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<td>CAD</td>
<td>Computer Aided Design</td>
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<td>CNC</td>
<td>Computer Numerical Control</td>
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<td>CPK</td>
<td>Process Capability Index</td>
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<td>CUI</td>
<td>Common User Interface</td>
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<tr>
<td>DoA</td>
<td>Description of the Action</td>
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<td>DoW</td>
<td>Description of Work</td>
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<td>EC</td>
<td>European Commission</td>
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<td>EEN</td>
<td>Execution Environment Node</td>
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<td>EFFRA</td>
<td>European Factories of the Future Research Association</td>
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<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<td>EU</td>
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<td>FoF</td>
<td>Factories of the Future</td>
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<tr>
<td>GD&amp;T</td>
<td>Geometrical Dimensions and Tolerances</td>
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<td>GUI</td>
<td>Graphical User Interface</td>
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<td>H2020</td>
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<td>HMI</td>
<td>Human-Machine Interface</td>
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<td>HTTP</td>
<td>Hypertext Transfer Protocol</td>
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<td>IEC</td>
<td>International Electrotechnical Commission</td>
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<td>IEC 61131</td>
<td>IEC standard for programmable controllers</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>IPR</td>
<td>Intellectual Property Rights</td>
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<td>JOA</td>
<td>Joint Ownership Agreement</td>
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<td>Term</td>
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<td>KPI</td>
<td>Key Process Indicator</td>
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<td>LBMC</td>
<td>Lean Business Model Canvas</td>
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<td>LR</td>
<td>Logistic Regression</td>
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<td>MPC</td>
<td>Model Predictive Control</td>
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<td>NC</td>
<td>Numerical Control</td>
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<tr>
<td>OEE</td>
<td>Overall Equipment Effectiveness</td>
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<td>OEM</td>
<td>Original Equipment Manufacturer</td>
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<td>OLO</td>
<td>On Line Optimization</td>
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<td>OPC</td>
<td>Open Platform Communications</td>
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<td>OPC UA</td>
<td>OPC Unified Architecture</td>
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<tr>
<td>OPI</td>
<td>Overall Performance Indicators</td>
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<tr>
<td>OS</td>
<td>Operating System</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
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<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
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<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
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<tr>
<td>PLSR</td>
<td>Partial Least Square Regression</td>
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<td>PO</td>
<td>Project Officer</td>
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<td>Quality Assurance</td>
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<td>R&amp;D</td>
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<td>ROI</td>
<td>Return on Investment</td>
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<td>RPO</td>
<td>Realtime Process Optimization</td>
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<td>Real Time Optimization</td>
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<td>SC</td>
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<td>Supervisory Control and Data Acquisition</td>
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<td>Small and Medium Enterprises</td>
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<td>SO</td>
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<td>SoA</td>
<td>State-of-the-Art</td>
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<td>SPC</td>
<td>Statistical Process Control</td>
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<td>SW</td>
<td>Software</td>
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<td>SWOT</td>
<td>Strengths, Weakness, Opportunities and Threats</td>
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<td>TCP</td>
<td>Tool Center Point</td>
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<td>TO</td>
<td>Technical Objective</td>
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<td>TRL</td>
<td>Technology Readiness Level</td>
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<td>UC</td>
<td>Use Case</td>
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<td>UI</td>
<td>User Interface</td>
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<td>WP</td>
<td>Work Package</td>
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<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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<td>ZD</td>
<td>Zero Defect</td>
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<td>Zero-Defect Manufacturing</td>
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1 Summary

This deliverable titled “D2.3 Deburring remanufacturing approaches” presents the achievements accomplished during task T2.3. The goal of this task was the development of a new concept of intelligent robotic deburring cell implementing Z-Fact0r’s Zero Defect strategies and resulting in a Z-REPAIR self-contained component including a new generation of high accuracy deburring spindles.

This report describes the work done and the 8 main innovations developed, namely:

I. A method for assessing the robot motion accuracy to improve the final accuracy of the robot deburring process.

II. A method to post-process robot trajectories and control logics in order to predictively compensate their motion accuracy errors and generate more accurate, first time right robot deburring, avoiding current State-of-the-Art long tuning processes which heavily reduce overall productivity and potentiate costs due to defects and scraps.

III. A metrology-based solution to detect the real pose of the part to be deburred and a method to refine and calibrate the robot code, in order to eliminate the inevitable accuracy errors that occur when picking the workpiece.

IV. Metrological on-line inspection tools to evaluate product quality at each deburring stage, identifying defects, and generating proper triggering messages to the supervisory control which enable the optimizer to develop proper manufacturing sequences and repairing actions.

V. A novel architecture for deburring spindles, with online monitoring of the spindle parameters and the compliance status, in order to monitor the process and automatically adapt to unpredicted conditions which would generate further defects.

VI. An object-oriented, IEC-61131 compliant, supervisory control architecture, as well as its integration with parametrized robot control code, which enables the on-line full reconfigurability of the intelligent robotic deburring cell.

VII. A ZD Robotic Process Planner, which, embedding the knowledge of the deburring process, is able to interpret the robotic cell sensory input and automatically generate an optimized deburring cycle, choosing the best tools and setting the ideal working parameters. Finally, such optimized deburring cycles are automatically translated into PLC and robot code and sent with IoT technology to the target controllers for an online process reconfiguration and ZD repair.

VIII. A novel architecture of intelligent robotic deburring cells, modular and reconfigurable, for the intelligent precision deburring of high end mechanical parts.

The document initially describes the State-of-the-Art of robotic deburring systems and the challenge to cope with (Chapter 3), followed by the chapter 4 that introduces the ZD intelligent robotic concepts and the Z-Fact0r strategy. Chapter 5 describes in detail the innovations developed within this project and the work done for their deployment. Chapter 6 deals with the SIR ZD Intelligent robotic cell, whose prototype will be finally integrated and demonstrated at TRL6.
2 Introduction

The five strategies (Figure 1) developed in Z-Fact0r project are directly addressed to customer needs of maximizing the quality of their products. Each of the strategies, as the name suggests, serves a different role which act synergistically with the others.

Specifically, Z-REPAIR strategy, is related to the capability to automatically repair the occurred defects without perturbing the overall production flow, with the minimum time and effort and assuring the best productivity and production flow. This means that the Z-REPAIR component, thanks to a model-based control embedding the knowledge of the process, has to be able to interpret the sensory input, identifying the occurrence of defects in order to automatically generate an appropriate manufacturing cycle able to repair and compensate the errors and defects sensed by choosing the best tools and setting the ideal working parameters based on the defect type and magnitude.

This deliverable is about deburring remanufacturing approaches, since the market requires at the same time high precision and productivity, achievable only with numerical controls (NC), together with the flexibility and adaptive touch typical of expert human operators. In fact, deburring is actually a repairing operation, in which the burrs are machining defects that must be eliminated.

A major challenge is related with the fact that burrs appear quite randomly and with different and variable thickness, then the best quality can be achieved only by specifically defining for each workpiece the optimal tools, paths and cutting parameters. Then, deburring is a multi-tool, multi-stage process in which complex sequences of operations must be performed, ideally defining and tuning each operation after evaluated the results achieved with the previous one. For such reasons, expert human operators have the experience and skills necessary to identify the deburring zones, the operations to be performed and the tools needed, furthermore, they continuously visually
inspect the workpiece, adapting their work to achieve the necessary quality and avoiding defects. Unfortunately, next generation of high-end mechanical parts, in particular in the aerospace and automotive field, must be realized with accuracy specifications that often exceed the accuracy achievable by human operators, then CNC or automated solutions are absolutely necessary.

At State-of-the-Art, robotic deburring has proved to be cost effective and accurate, having the potential to achieve the desired performance for medium accuracy needs, but it still needs to be improved to be applicable to the most demanding requirements of the leading edge of the manufacturing sectors, in fact it should embed the process knowledge for autonomously plan optimized deburring cycles as well as for monitoring and repairing incoming defects.

Therefore, to satisfy the increasing customer needs, Z-Fact0r Project aims at developing a novel concept of intelligent robotic deburring cells, implementing Z-Fact0r's ZD strategies in which metrological quality control is integrated into the manufacturing process to achieve the best quality even in presence of heavy process variations. In addition, after a preliminary quality assessment, the model based supervisory control, embedding the deburring process knowledge will generate a custom multi-stage manufacturing cycle with specific compliant tools.

Accurate process monitoring and final metrological quality control enables early detection of incoming defects at each stage and will be used as process feedback to verify the quality of the work or further repairing actions. At each stage the results will be used to verify the quality, recording the performance achieved and if needed, triggering alarms. Finally, the Z-REPAIR intelligent deburring techniques will be carried out experimentally on a robotic deburring prototype at TRL 6.
3 Robotic Deburring

3.1 Problem formulation

A burr is defined as an undesirable effect generated at the edge of a workpiece after the machining process, but can also be generated during casting, forging, sintering, welding, cutting, plating, and painting [1]. Deburring is the process to remove sharp edges or burrs, smoothing surfaces of metal or plastic components resulting from manufacturing or casting processes. The deburring tool could be small and a part with many small/accurate details is hard to be reached by a CNC machine. In addition, manual deburring and chamfering of parts by a human operator could be up to 10% of the total machining time of a product. Hence, a good solution is to use an industrial robot to perform the deburring process [2].

Nowadays the use of industrial robots has taken hold in many fields and recently robotic systems are also performing more value-added tasks like cutting, machining, deburring and polishing. Due to their low cost architecture and intrinsic controllers’ limitations, industrial robots are well suited to perform repetitive tasks with limited accuracy, but proper intelligent ZD manufacturing strategies may exploit industrial robots’ potential to more demanding applications. In particular, there would be a great potential for processes like deburring and deflashing, which are commonly carried out only by expert human operators because of the need to develop manufacturing cycles specific for each single workpiece. In fact, the main purpose of robotic systems’ application in finishing tasks like deburring and deflashing is to solve manufacturing processes that traditionally have been carried out by manual operations.

Innovation 8 of Z-Fact0r Project is “Deburring technique using robotic arms”: deburring is a strategic manufacturing operation that requires ever-increasing precision, not effectively achievable by human operators, but with the adaptive and flexible process planning approach typical of expert human operators. In fact, burrs appear quite randomly and with different and variable thickness, then custom tools and paths should be defined specifically for each workpiece.

Robotic deburring is cost effective and potentially able to achieve the desired performance for average accuracy needs, but it needs to be heavily improved to be applicable to the most demanding requirements of the leading edge of the manufacturing sectors.

Actually, at State-of-the-art, robotic deburring processes are programmed to perform the deburring in the worst case possible, then, robots paths and trajectories are defined to contour all the edges where burrs can occur and with the feed rate necessary to cut the thickest burrs. Such approach is definitely robust but it leads not only to higher costs and (much) longer cycle times, but also to possible defects: in fact, when breaking edges without burrs it may happen to cut more than allowed, leading to scrap (in this case the only repairing action would be to add material with cladding techniques and repeat all the mechanical machining).

Current research supports that the only solution is to define long, much less productive, deburring cycles in order to be sure to deburr all the edges/surfaces despite the real presence of the burrs, but this may leads itself to defects and scraps. It is common the need of costly manual refining and repairing actions to finish the deburring process. This leads to high
costs, lower productivity and a relevant number of scraps and wastes. To achieve ZD, defects should not only be predicted and prevented/avoided, but also detected, managed and repaired. Therefore, even if the robotic deburring cells successfully automated many average applications, the most demanding manufacturing sectors, base of the European manufacturing competitive edge, strongly need ZD robotic deburring solutions, in which knowledge driven supervisory control adds robots the intelligence to develop custom deburring cycles, achieving the best quality and repairing online any occurred defect.

Some major advantages of robotic deburring are:

- Low cost, adaptive, and reconfigurable, flexible open control with possible integration of extended sensory feedback.
- Industrial Robots are able to manufacture pieces with complex shapes and difficult access, dispensing with devices and special production techniques necessary to carry out manufacturing process in conventional machine.
- Possibility to reach very large working volume.
- High flexibility, which means that the robot could be used not only for one scope and it is easy to modify the process if the production plan needs it.
- High repeatability, which makes industrial robots perfect to replace people in recurring task and move human contribution at a higher level.

The main limitations and sources of defects in robotic deburring are:

1. **Robots motion accuracy**: robots’ limited motion accuracy leads to paths and trajectories errors, which compromise the final deburring quality. Main sources of errors are the robot reducers friction and backlash, as well as the overall robot geometrical accuracy. Properly designed tool compliance systems can mitigate the effect of such motion accuracy errors but defects are still occurring. To achieve the desired accuracy, even with latest robot simulation and offline programming tools (e.g. Delmia robotics, ABB Robotstudio, Siemens Process Simulate) long manual refining and tuning is needed, leading to wasted workpieces and precious time, inhibiting a fully reconfigurable and flexible production needed by the automotive/European FoF manufacturing. Since last generation deburring processes require superior accuracy (typically in the order the robot repeatability), accurate calibration and predictive compensation should be performed, in order to improve the robot final accuracy up to its current repeatability values.

2. **Workpiece variations and pose accuracy**: burr presence and thickness variations lead to unpredictable defects that often generate scraps and wastes, in fact, as already written, due to the different process conditions, the burrs’ formation is unpredictable and occurs quite randomly. Furthermore, it may also happen that the robot picks the workpieces with slightly different poses, which can compromise the overall deburring accuracy. To achieve such accuracy, it is necessary to develop specific custom iterative deburring cycles, in which the robot machines only the zones in which the burrs are really present, with a subsequent check of the quality achieved in order to repair progressively the errors and defects.
3.2 Robotic deburring cells

There are two main types of robotic deburring cell architecture:

1. **Tool-in-hand:** In these applications (Figure 2), a compliant tool is mounted on the robot and manipulated over the part to be finished. The part is fixed. Tool in Hand configurations are used where the part to be finished is too large or too heavy for a robot to carry [3], main limitations are the cycle time since changing the tool is time consuming.

2. **Part-in-hand:** the workpiece is picked up by the robot with a gripping system, while several deburring tools are fixed as auxiliary devices; the robot manipulates the workpiece to be deburred as result of contact between the work piece and the tool. Part in hand applications (Figure 3) are most often used when the part to be finished is relatively small (comparing with deburring/grinding/polishing tool’s size). The *part in hand* approach offers some advantages over the tool-in-hand. Often, load, unload, packaging or other operations can be combined with finishing/deburring operations on a single work station, so doubling up these operations can provide a much greater productivity and return on investment [3].

![Figure 2: “Tool-in-hand” configuration (SIR S.P.A.)](image-url)
A typical robotic deburring cell is a complete manufacturing integrated system that is composed of:

- A mechanically closed safety structure which contains all the devices with the purpose of protect human operators during the process.
- One or more Industrial Robots.
- A PLC to lead all the devices and control the process through the I/O signals.
- One or more rotating tables/conveyors to feed in raw parts and take out finished parts.
- A tool stand equipped with different grippers and tools depending on how many different parts or feature have to be processed.
- A refining/calibration station equipped with by touch probe or digital gauge.
- A working zone, that in the case of a part-in-hand solution presents a multi-tools station, otherwise in a tool-in-hand solution there is a customized station to block, move and rotate the part that has to be worked.
- Many types of sensors to control the process.
- Sometimes, if required by the application, it could be a vision system to recognize presence, position and orientation of parts.

Some applications need specific equipment, such as seventh axis slide, indexing table, force sensor, and vision system that can increase the functionality and flexibility of the work cell [3].
3.3 **Online and offline Programming**

The most popular method of robot programming is probably the online one based on the use of a teach pendant, which is a touchscreen tablet that directly interfaces the operator with the robot. To program the robot, the operator moves it from point-to-point and save each position individually. When the whole program has been learned, the robot can play back the points at full speed.

**Advantages:**

- Most traditional industrial robots come with a teach pendant, which makes them familiar to technicians.
- Robot can be programmed using the real position of devices and parts.

**Disadvantages:**

- Disruptive to the whole system due to robot downtime. The robot must be put into "teach mode" and all operations using the robot halted until it has been programmed.
- Production must be suspended during online programming.
- Online programming can start only after the whole robotic cell has been developed.

Offline programming is the technique of running models in a purely stand-alone format, not connected to any hardware and normally not run in Real-Time. This approach enables the user to program robot motions in a simulated environment before the production of the real one has been started. Moreover, the programmer and the mechanical designer are able to find the best layout and to solve problems in the early stage of the project that results in cost and time reduction [2].

**Advantages:**

- Programming stage could start before or in parallel with the development of the equipment with relevant time and cost reduction.
- An existing system could be programmed for new tasks without stopping the production.
- Programs could be set up using CAD files saving time.
- Libraries with standard components and procedures can be created.

**Disadvantages:**

- Requires a simulation software and skilled people to implement simulations.
- Requires to be online checked and corrected.

Talking about robotic deburring cells, offline programming and simulations allow reducing drastically programming time. Indeed, the deburring process is a sequence of complex trajectory, which are easy to program using the 3D model of the part in a simulated environment, as well as it is very difficult to do online.

Of course, the simulation does not replicate the real environment at 100% and it is mandatory to calibrate, check and correct the program online.
4 Z-REPAIR – Zero-Defect Intelligent Robotic Deburring

4.1 General concept and challenges

The aim of the present work is the development of a novel architecture of intelligent robotic deburring cells, which will be able to perform ZD repair actions thanks to Z-Fact0r’s ZD strategies. In particular, thanks to a novel architecture of model based supervisory control, the robotic cells must be able to identify defects and autonomously develop optimal custom deburring cycles to repair them while continuously monitoring the quality. In fact, thanks to a model based control embedding the knowledge of the deburring process, the Z-Fact0r repair component should be able to mimic and emulate expert human operators, by iteratively checking the quality and the defects and developing optimal repairing manufacturing sequence of operations. The Robot cell supervisory control will be then able to automatically generate the multi-stage deburring cycle once sensed the quality achieved after each deburring stage.

The solution is focused on robotic precision deburring since it has major market impact, in fact, at State-of-the-Art there is no feasible solution for the high-end applications.

Nevertheless, the Z-Fact0r remanufacturing and repair application could be later customized and configured to be applied also in other applications.

As already written, the main challenges are related with the overall final accuracy achievable with robotic systems, as well as with the heavy variations of the process and components quality, which impose the need to develop an inferential engine able to generate singularly optimized custom sequence of operations, dynamically monitored to assess the quality achieved and identify further repairing actions. An important, often underestimated technological challenge is related with the need to integrate such knowledge based optimization engine with State-of-the-Art control architectures, namely PLC and Robot controllers, which have strong limitations.

4.2 Z-Fact0r's ZD Strategy Implementation

The Z-REPAIR component implements the Z-Fact0r’s ZD strategy, based on superior predictive planning with prevention defects, accurate detection of defects or potential defect occurrence, continuous process monitoring.
The Z-REPAIR strategy of intelligent robotic deburring architecture (Figure 4) is based on offline components, connected with the robotic cell with IoT technology and online and real-time components, directly integrated with the PLCs and robot controllers.
Superior accuracy behavioural models of the robots, peripheral equipment and deburring process provide a realistic and accurate prediction of the final performance achievable by the robotic deburring cell and are used to build robust, defects-free, first-time-right, processes. Due to their complexity, such models cannot run in real-time, but are fundamental to develop the knowledge base for each product and workpiece to be deburred with Zero Defect. For example, a digital twin coupled to the robotic cell will allow to develop more accurate robot trajectories and deburring operations, drastically reducing the occurrence of the defects and virtually eliminating the long process tuning, usually needed to refine the process (in which many defects are created, often...
leading to scraps that heavily reduce the productivity and profitability of the robotic cells). Then, since it is possible to plan operations first-time-right, the repairing actions will be much more effective and reliable. The offline models are then used to create a knowledge-base, which is accessed by the online (i.e.: integrated with the cell’s PLC and Robot controls) Z-REPAIR components. In particular, specific robot cells’ sensors will perform continuous monitoring of the process, identifying defects and detecting critical situations, leading the Z-REPAIR optimizer to generate specific, singularly optimized, sequences of operations suited to compensate and eliminate the defects.

A modular, incremental approach has been followed to develop the final Z-REPAIR implementation, in order to build a solid knowledge base, supported by experimental validation, initially performed on an existing research cell to reduce the costs, which will be finally integrated into a demo cell for final demonstration and validation.

The following table (Table 1) summarizes the implementation steps followed to develop the Z-REPAIR Component implementing Z-Fact0r’s ZD strategies.

Table 1 Z-REPAIR component implementation steps

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<th>Step 1 - Simple</th>
<th>Step 2 - Optimized</th>
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<td><strong>Process Parameterization and Optimization</strong> (Z-Repair)</td>
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5 ZD-REPAIR – Zero-Defect Intelligent Robotic Deburring innovations

5.1 Introduction
The Z-REPAIR – Zero-Defect Intelligent Robotic Deburring, and its implementation into the Innovation 8 of Z-Fact0r Project have required the development of the following main enabling innovations:

1. A method for assessing the robot motion accuracy to improve the final accuracy of the robot deburring process.
2. A method to post-process robot trajectories and control logics in order to predictively compensate their motion accuracy errors and generate more accurate, first-time-right robot deburring, avoiding State-of-the-Art long tuning processes which heavily reduce the overall productivity and costly bring to defects and scraps.
3. A metrology-based solution to detect the real pose of the part to be deburred and a method to refine and calibrate the robot code, in order to eliminate the inevitable accuracy errors that occur when picking the workpiece.
4. Metrological on-line inspection tools to evaluate product quality at each deburring stage identifying defects, and generating proper triggering messages to the supervisory control which enable the optimizer to develop proper manufacturing sequences and repairing actions.
5. A novel architecture for deburring spindles, with online monitoring of the spindle parameters and the compliance status, in order to monitor the process and automatically adapt to unpredicted conditions which would generate further defects.
6. An object-oriented, IEC-61131 compliant, supervisory control architecture, as well as its integration with parametrized robot control code, which enables the on-line full reconfigurability of the intelligent robotic deburring cell.
7. A ZD Robotic Process Planner, which, embedding the knowledge of the deburring process, is able to interpret the robotic cell sensory input and automatically generate an optimized deburring cycle, choosing the best tools and setting the ideal working parameters. Finally, such optimized deburring cycles are automatically translated into PLC and robot code and sent with IoT technology to the target controllers for an online process reconfiguration and ZD repair.
8. A novel architecture of intelligent robotic deburring cells, modular and reconfigurable, for the intelligent precision deburring of high end mechanical parts.

Such innovations will be successively demonstrated and validated at TRL 6.

5.2 Robot motion accuracy
Robots limited motion accuracy is one of the main sources of defects and overall productivity loss. In fact, when automating complex operations like precision deburring, the robot motions deviations require the operators to experimentally validate the process, testing the robot operations on several workpieces, which usually become scrafs due to the excessive defects. Such drawback would inhibit a real ZD intelligent deburring cell, since the repairing actions and paths
should be carefully validated on the real cell, this should require an enormous and unacceptable amount of work.

As a first step, an accurate analysis and experimental assessment of the robots real accuracy has been performed. A method for assessing the robot motion accuracy has been developed. In fact, most of the studies and solutions available are focused on measuring and analysing the robots positional accuracy, however, when dealing with delicate processes like deburring, also the speed and motion profiles must be evaluated. As measuring tool, a FARO CAM2 Laser Tracker (Figure 5) has been chosen for its accuracy and versatility, the measurements have been made on a ABB IRB 2400 robot, best suited for precision deburring.

Unfortunately, the proprietary FARO data acquisition software provided (CAM2 Measure 10) is not suited to perform dynamic measurements, then it was necessary to exploit the FARO SDK available for developing a tool able to connect with the tracker controller and acquire dynamically the data at 400Hz. Such tool is also synchronized with the robot with a trigger PLC signal.

A vast experimental campaign has then been performed, evaluating the robot motion accuracy on different paths, at different speeds. The contributions of each robot joint have also been evaluated to identify possible sources of motion accuracy errors.

In the following figures (Figure 6 - Figure 9) an outlook of the results can be depicted, in particular, it must be noted that, while the mean errors are comprised within 0.1-0.2mm, the spread is much higher, achieving even more than 2mm, which might bring further defects instead of repair. Even if it is based on an expensive laser tracker, such method has proved to be effective and powerful, providing also important information for the best location of the robot and deburring station.

The approach proposed benefit also the huge work done in the FP7 project COMET [4], in which it has been investigated the robot accuracy for milling, then focusing on the robot stiffness, beside
the methods proposed resulted too heavy and non-practical for the precision deburring. In the case of deburring, the main motion accuracy error sources have been identified as the reducer backlash and stiction, while the joint compliance was judged negligible.

Once assessed the errors sources, and their estimated effects on the robot accuracy, it has been possible to develop a series of algorithms, which compensate predictively the robot motion errors when the motion errors sources are identified. Such set of algorithms has been saved in a C# library for future use.

Figure 6 robot mean accuracy errors in X direction
Figure 7: Robot mean accuracy errors in Y direction

Figure 8: Robot mean accuracy errors in Z direction
Then, the subsequent work has focused on the development of a method to post-process robot trajectories and their control logics, in order to predictively compensate their motion accuracy errors by using the aforementioned library and algorithms. Using the robot simulation and offline programming ABB RobotStudio, it has been possible to extract the exact motion of each robot joint, since a correct identification of the sources must be performed in the joint space. By analysing the final joint motion and identifying the motion error sources, the robot control logics can then be modified with the predictive compensation of the motion errors, providing then the chance to generate much better robot trajectories and processes. This is the foundation for developing real robot ZD processes, since it heavily improves the final robot accuracy, eliminating many sources of defect. In fact, in order to provide a real and effective Z-REPAIR, the generated repairing actions must be accurate and effective enough to avoid the need of a physical validation and this can be performed only with a Digital twin approach.

A validation of the solution developed has proved its validity, while further validation will be performed during the demonstration activities.
5.3 Robot calibration and Part Refining

Other major sources of accuracy loss are related with the exact position of the numerous reference frames present in a robotic cell. In fact, each robot program relies on several reference frames, and any error regarding their real coordinates will introduce offset and orientation errors. In particular, the “world frame” is the robot absolute reference, the “base frame” is the reference system located in the robot zero position, on the fixed base of the robot, and the control logics natively refer to it.

![Figure 10 Tool and workpiece reference frames](image)

The “wrist frame” is located on the robot Tool Center Point (TCP) flange, while for the end effectors, tools and workpieces further reference frames are defined. As it is easy to understand, each reference frame transformation brings errors and a proper calibration is needed. In literature, many works have investigated this issue [5], and cell calibration techniques are available. Following the recent literature, a practical method for a fast and effective online calibration has been developed and implemented on a self-contained robot code, which allow an automatic robot calibration with the only need of a metrological touch probe and/or linear gauge. In this way, a refinement of the exact position of the tool and end effector can be automatically provided, avoiding further defects and providing the necessary accuracy to perform effective and first-time-right repairing actions.

Nevertheless, another major source of accuracy error is related with the exact position of the workpiece with respect to the end effector. In fact, especially when the workpiece gripping zone is located in rough, non-machined areas, it happens that the workpiece can be picked on a
different position or with different orientation. To this purpose, a metrology-based solution has been developed, in order to detect the real pose of the part to be deburred.

Different solutions have been investigated and designed, choosing metrology touch probes as well as linear gauges that sense the datum of the workpiece and the end effector (gripper). A refining station has been finally designed (Figure 11).

Finally, a set of algorithms and sensing strategies have been developed, a main challenge has initially been related with the robot controller delay, which provided wrong information on the TCP position, while a set of fast and effective algorithms, suited to be processed by the robot controller, have been conceived and tested. The final result is a library of refining and calibrating functions written in ABB RAPID language which allow the online refinement of the workpiece frame (work-object) which eliminated the inevitable accuracy errors occurring when picking the workpiece.

Experimental tests, initially performed with simple geometry specimens and later with mechanical parts have confirmed the validity of the algorithms and supported the improvement of the station. Different level of errors was detected and the refinements proved to be effective.
5.4 Defects identification

A crucial repairing task is related with the identification of the defects, in particular, for deburring it is fundamental the identification of the presence of burrs, in order to generate specific deburring operations only on the profiles where the burrs are. In fact, as already written, deburring edges without burrs would not only be a loss of time, but it also may generate itself defects, cutting over the tolerance admitted. Furthermore, the entity of the burrs should be analysed, in order to choose the proper tools and assign the appropriate feed rate.

The previous innovations provided the capacity to perform accurate, first-time-right and well-tuned deburring operations, the defects’ identification enables the identification defining the proper optimal sequence of deburring operations. After each deburring stage, the defect identification will be performed to assess quality achieved in order to better tune the next operation or, in the worst case, define a proper repairing action.

Then, accurate evaluations on the possible sensors have been carried out. Due to the sensitiveness of the workpieces, non-contact sensors have been preferred, and, in particular, optical sensors. Different vendors’ vision systems and scanners have been tested on several aluminium profiles, cut with different levels of accuracy (Figure 12) and chosen also to reduce the costs.

![Figure 12 Aluminium profiles specimen](image)

Image processing techniques (Figure 13) have been developed to identify edges, which, compared to the ideal profiles enable a first identification of rough profiles or burrs, that can be associated to tools and different feed rates. The sensitiveness to different light conditions and materials have been evaluated, as well as the processing time. Point clouds processing has proved to be more precise even if more time consuming and with a higher level of rumour.

The results achieved have been judged positively and a quality control station module has been designed and developed to be integrated within the cell.

The solutions developed are now being evaluated for a possible patent.
5.5 Precision deburring spindles and tools

A custom deburring station and spindles have been designed in order to improve the cutting process and a constant and uniform contact pressure to profiles even in case of complex geometries.

Different compliance solutions (radial, axial, planar, angular and omni-directional) have been identified and developed for assuring adaptive compensation also in presence of misalignments and accuracy errors, in order to provide and effective repairing action. The compliance solutions have been optimized to reduce friction and assure an effective damping, in order to assure a constant contact to the workpiece also in the odd case of unexpected burrs and bad programming, in order to further improve the effectiveness and final quality of the deburring.

Specific regulating devices have been designed and optimized with multibody simulations to adjust and provide optimal compensation pressure (which can be modified point by point during execution of the path) internal pressurisation, lubrication and constant wetting of the cutting tools.
Proper seals with minimal frictions have been conceived to assure the best operating spindle conditions, reducing wear and possible failures.

The spindle’s compliance final sensitivity allows optimizing the cutting process by changing the compensation pressure by just a few tenths of a bar, enabling a fine tuning far superior than State-of-the-Art.

Tool accessibility and reduced inertia have been assured with shape optimizations, in order to obtain a compact and slim design (Figure 14). The SIR pneumatic spindles are suited to cut a wide variety of materials, reaching 100,000 rpm. Finally, an extended study on the tools available and different deburring solutions.

The novel architecture of the spindle is now being evaluated for a possible patent.

Furthermore, a novel modular, multi-tool deburring station has been developed (Figure 15). Since deburring is intrinsically a multi-stage and multi-tool process, the time needed to change tool is usually of the same order of the deburring operation and it heavily reduces the overall final productivity. In order to mitigate such problem, a multi-tool station has been designed: the station has 5 modular docks in which are assembled ready-to-use deburring tools, which can be quickly positioned in the working area where the robot is manipulating the workpiece. Such solution not only heavily improves the productivity and profitability of the overall robotic deburring process, but it is also useful for the final working accuracy, since each tool can finally work in the same working area, calibrated for the robot final accuracy.

Relatively to previous solutions already developed by SIR, the multi-tool deburring station instead of adopting an indexer uses an external servo-axis to assure the best accessibility. The novel servo-position station adopts a zero-backlash compact harmonic drive servo-actuator connected
with Ethercat fieldbus to the cell supervisor control. The servo-positioned deburring station can then position each specific tool in the most suitable place or can move dynamically the tools, interpolating with the robot controller with a task time of 12ms.

Experimental validation confirmed the effectiveness of the solutions and during the test the deburring station proved to be more flexible and eased the development of the deburring process.

5.6 **Object-Oriented modular Control Architecture**

The control architecture plays the key role for an effective, working in industrial environments, ZD intelligent robotic deburring. In fact, as told, since it is necessary to **continuously calculate and generate new sequences and operations specific for each workpiece**, an industrial grade feasible solution should not rely (for both technical and financial reasons) on massive programming and validation as it is State-of-the-Art practice, in any case, it would be very
demanding to predict all the possible situations. Another major issue is the intrinsic complexity of the control architecture, which is usually de-located on several controllers and fieldbuses. In fact, at State-of-the-Art, the robotic cell programming is distributed on the robot controllers, device controllers and supervised by one or more PLCs. In particular, for the basic innovations previously described, even with only one robot, a generic cell would be based on a robot controller, a motion controller, a PLC and an industrial PC (Figure 16), while, due to vendor specifications, the communications would be transmitted on three different fieldbuses (Ethercat, Profibus/Profinet and CAN).

State-of-the-Art robotic cells control logics are developed assigning part of the controls to the robots controllers (written with Robot vendors proprietary languages) and part to the PLCs and other controllers.

![Figure 16 robotic cell's controllers connections](image)

This often follows the electrical connections between devices, sensors, actuators, and other I/Os, which, however, are carried out focusing mainly on the wirings. Such empirical approach has shown severe limitations when increasing the number of devices and the complexity of the robotic processes, only partially solved with complex and time-consuming validations, often leading to avoiding to add further intelligence to the robotic cell. Therefore, the autonomous behaviour of robotic cells has been limited only to a rigid parametrization of the code, which however would not achieve the expectations needed for a real intelligent ZD robotic deburring.

In Z-Fact0r task T2.3, sophisticated software engineering methods, together with the latest features offered by the IEC-61131 standard, have been investigated, and a novel control architecture has been developed. Such control architecture is structured hierarchically (Figure 17), with a supervisory PLC processing the I/Os and coordinating all the devices and controllers, while activating agents and methods. The main PLC, in turn, could be connected with industrial Ethernet or IoT technology with a PC (local or on the cloud), where the high-end optimization algorithms and software tools might run on their suitable OS and platform. The PC will
operate remotely, sending batches of results of the optimized sequence of operations, parameters and validated code for the target controllers.

Such approach required a long work, in which many different solutions and configurations have been tested and compared in terms of performance, robustness, code re-usability, but at the end, a reliable platform has been developed. Each device is coupled to a dedicated object and the related methods, a hardware abstraction layer provides reusability of the same code for different devices performing similar tasks, with a strong level of modularity, reusability and reliability. IOs variables are directly accessible also by the main PLC coordinator, exploiting fieldbuses and couplers (Figure 18). Finally, special standard interfaces have been developed to ease the integration and connections between the different modules; even if the final code is heavier (but mostly available, then already written and validated) no noticeable loss of performance has been observed.

Such modular and configurable approach finally enables the automatic generation of optimized deburring sequences, calculated by external optimization engines from product specifications and quality status (measured by the cell sensors) and constraints. Parts of the codes are still parametrized, but the parameters are variables optimized by the coordinator PLC or the external PC software tools.

Figure 17 controllers hierarchical architecture
With such control architecture (Figure 19), optimization can be done on a high performance industrial PC (or even on the cloud) where complex models embedding the knowledge of the deburring process are processed to generate optimized code for the different target controllers.

**With the developed control system architecture and control code platform, the process sequences and knowledge are resident in the main, modular, object-oriented code, which automatically generates validated robot code and device controllers instructions.**
The implementation and validation of the novel control architecture has clearly shown its performance superiority with respect to the State-of-the-Art, also proving an elevate level of reusability.

5.7 **ZD intelligent robotic deburring process planner**

The last Z-Fact0r project innovation developed in task 2.3 is a **ZD robotic deburring process planner**, which, embedding the knowledge of the deburring process and repairing actions, is able to interpret the robotic cell sensory input and automatically generate an optimized deburring cycle, choosing the best tools and setting the ideal working parameters. Finally, such optimized deburring cycles are automatically translated into PLC and validated robot code for the innovative Object-Oriented modular control architecture. Such robotic deburring process planner is natively conceived to be interfaced with the defect detection modules, which iteratively, after each pass of deburring operations, will evaluate the quality achieved and the need of further repairing actions. The triggers action identified by the defects detection module are automatically interpreted, calculating the optimal deburring tools, as well as their best operating parameters.

The deburring process planner is also integrated with a robotic cell digital twin, which allows to evaluate the robot motion final accuracy and avoid generate accurate, defects-free robot trajectories and control logics.

Given the workpiece to deburr, a nominal and generic deburring cycle is generated and validated on the digital twin (Figure 20), such nominal and generic deburring cycle is the more conservative deburring cycle, conceived for the worst case, as presented in State-of-the-Art. Using the robot post-processor described in paragraph 5.2 robot motion errors are compensated predictively, in order to limit and avoid the generation of further defects during the repairing actions.
The robot nominal and generic deburring cycle is then segmented into modular simple robot tasks, whose fine motions are validated on the digital twin, with a quick final calibration on the real cell. Such robot tasks are automatically named and can be accessed when the corresponding trigger events on the quality control and defects detection are activated.

Once identified the process sequential constraints and working parameters, the Z-Fact0r’s ZD robotic deburring process planner (Figure 21) evaluates the cell resources availability and the defects detected by the online quality control station. Then, it automatically generates all the possible and feasible sequence of operations, calculating the most performing, in order to reduce the final cycle time and performing only the necessary operations needed to repair the defects sensed.

Finally, the optimal sequence of operations is validated on the digital twin and the related control logics, automatically generated, are sent to the main supervisor PLC, the robot controller and the other device controllers.

Such robotic deburring process planner allows to emulate the expert human operators unique capability to adapt to each possible situation and calculate the proper optimal repairing sequence of operations which can lead to repair the defects and achieve the desired quality by customizing the overall deburring cycle and operations.
Experimental tests and validations have shown a great potential but still need further improvements, which will be refined during integration and demonstration.

5.8 **ZD intelligent robotic deburring repairing strategy**

Thanks to the Z-Fact0r's innovations previously described, novel ZD robotic deburring repairing strategies are finally enabled. In particular, **iterative quality control and defects identification allow the generation of custom, singularly optimized repairing sequence of operations.** Metrological on-line inspection evaluates product quality at each deburring stage and identifies the defects to be repaired. A novel ZD robotic deburring process planner, supported and validated by a digital twin of the robotic cell, interprets the sensory input and automatically generates an optimized deburring cycle, choosing the best tools and setting the ideal working parameters.

The related control logics for all the different controllers, in particular a main supervisor PLC that hierarchically coordinates the other controllers and the robot controllers, are automatically generated, validated and sent online to the target controllers. The Robot cell supervisory control is then able to automatically generate and perform the multi-stage deburring cycle once sensed the quality achieved. **After each deburring stage, the quality achieved is iteratively checked in order to better tune the next operation or, in the worst case, define a proper repairing action.**
In Figure 22 it is depicted the ZD intelligent robotic repairing strategy.

The process is composed of two main parts:

- The **preliminary offline simulation** of the robotic cell on a digital twin to develop a nominal and generic deburring cycle for the worst case situation, generated and validated on the robot cell digital twin. Such nominal and generic deburring cycle is the more conservative deburring cycle, conceived for the worst case, as generates all the robot’s procedures (movements, frames, target, parameters), to perform all the operations with
the defected part (picking, refining, work, rework, place, etc.), the correct operational sequence checking the collision avoidance;

- The **online process**, performed live and automatically by the robotic deburring cell (Figure 22) which is based on:
  
  o **Defected parts picking**: The parts to be reworked are randomly positioned on a feeder (e.g., a rotatory table). A vision system identifies the part locations and pose, sorting algorithms to associate the part to the proper gripping end-effector and provide the target coordinates for the picking. The robot gets the suggested gripping end effector and grip the part.
  
  o **Gripping refining**: the parts are picked up with grippers equipped with custom-designed fingers to ensure the highest repeatability, but the possible misalignments can introduce relative position error, still leading to defects, and should be measured and compensated. To this purpose, exploiting the innovation described in paragraph 5.3, a refining station equipped with metrological sensors senses the part and end effectors datums in order to calculate the real relative position of part respect the robot frame after picking, adjusting the reference frames and calibrating the trajectories.
  
  o **Quality Control and defect identification**: iterative quality control is performed before each deburring stage, exploiting the innovation described in paragraph 5.4, the system is able to detect if and which defects are present, as well as providing the information needed to choose the proper tool and its deburring process parameters.
  
  o **Process planning and process parameterization**: once the defects triggers are provided, the ZD intelligent robotic deburring process planner described in paragraph 5.7 calculates the custom optimal deburring cycle and the related control logics are automatically generated and sent to the corresponding target controllers. As written, the process planner can be located on the cloud or it can be resident in a local industrial PC (e.g. the same industrial PC in which PLC and HMI run).
  
  o **Deburring cycle**: during each operation of the custom deburring cycle relevant parameters are monitored and stored, especially if the novel compensated deburring spindles (described in paragraph 5.5) are used. Sensor based process monitoring will allow to perform proper repairing actions and detect potential dangerous situation, then further avoiding the occurrence of other defects or failure in the repair.
  
  o **Quality Control and defect identification**: at the end of each deburring stage iterative quality control is performed again, in order to check the results achieved with the previous repairing action and, if necessary, better tune the next operations or even re-calculate new repairing sequences.

The workflow repeats iteratively the quality control and defects identification task, the generation of the optimal deburring cycle and its realization until the quality assessment will sense that the repairing action has been completed successfully and no other defects are present.
The fundamental innovations described in this chapter realize and accomplish the objectives set in the Innovation 8 of the Z-Fact0r GA, as well as Z-Fact0r’s technical objective TO10 (“Develop strategies for product rework to repair defects”):

- Knowledge based tools able to predict sources of defects, namely motion and positional accuracy errors and tool contact conditions and pre-compensating actions to avoid and prevent the occurrence of defects: successfully achieved with the innovations described in the paragraphs 5.2, 5.3 and 5.5
- Metrological on-line inspection tools, which perform and integrate quality control in-between different deburring cycle stages; verify the quality of the work done, detect incoming or existing defects and trigger alarms to develop automatically “next stage” repairing actions: successfully achieved with the innovations described in the paragraphs 5.4 and 5.6 5.5
- Knowledge based tools, which automatically calculate proper, custom-optimized repairing actions to be performed in the next stages, successfully achieved with the innovations described in the paragraphs 5.5, 5.7, 5.6 and 5.8
- Inference engine, which provides a model of both the process and the detection of defects with the related compensating and repairing actions: successfully achieved with the innovations described in the paragraphs 5.2, 5.7 and 5.8
- A supervisor will be able to store the relevant information of each working cycle and upload it on the cloud for advanced analytics: successfully enabled by the innovations described in the paragraphs 5.6
- Robotic intelligent deburring techniques in which metrological quality control is integrated into the manufacturing process to achieve the best quality even in presence of heavy process variations: successfully achieved with the innovations described in the paragraph 5.8

The Z-REPAIR fundamental innovations have been conceived and developed with a clear application focus on ZD robotic intelligent deburring (build the Z-Fact0r’s Innovation 8 and achieve the technical Objective TO10) but, nevertheless, they can be configured and applied also for other Industry 4.0 manufacturing applications.

Such Z-Fact0r novel intelligent deburring robotic cell overcomes all the existing limitations of the State-of-the-Art of robotic deburring, creating new markets with a high industrial impact to be exploited.

The performance achieved and the preliminary experimental validations have been judged very satisfactorily by SIR, which foresees to further increase its turnover and market position.
6 SIR ZD Intelligent Robotic Deburring Demo-cell

6.1 General architecture

The modular components and technological innovations described in Chapter 5 have been developed following a system engineering approach, not only focused to build a general and configurable Z-REPAIR architecture and the related basic modules, but also for a real implementation on an industrial market relevant application (precision deburring).

Integration and demonstration will be fundamental to assess the real performance of the solutions developed. To this purpose, the general architecture of a future generation of robotic intelligent deburring cells has been developed, and a demo-cell will be realized.

SIR is currently market leader in the field of robotic precision deburring and foresees a strategic and important impact of the Z-Fact0r project.

In order to reduce the costs, such cell will be an evolution of an existing advanced robotic deburring research cell, recuperating some expensive major components (e.g.: the robot and some standard peripheral equipment) and adding the innovations developed in this task T2.3.

Such approach has been chosen not only for heavily reducing the costs and resources needed, but it will also permit to have a reference basis for a correct evaluation of the performance improvement achieved with respect to what is now recognized as the best in class.

This chapter will describe how it is equipped and which will be the general cycle of the robotic deburring demo-cell at SIR.

6.2 ZD robotic intelligent deburring Demo-cell

In Figure 23 it can be depicted the general architecture of the cell, implemented in the layout of the demo-cell.

Part Feeder

The part feeder is a classic rotary table feeder, but also different type of feeder can be used. To reduce the costs and time needed, the rotary table has the SIR standard design, while the wirings, electrical and logical connections have been fully re-designed, adopting the Z-Fact0r’s innovative control architecture described in paragraph 5.6. With such approach the logic of the feeder has been standardized and associated with hardware-independent methods, then if the feeder would be changed (e.g.: with a conveyor or other different solutions) the same software logics would be used.

The feeder has been designed for a fully flexible manufacturing with elevated product mix and lot-size-one, then raw parts are positioned randomly in the table, a vision system, with SIR proprietary technology, will identify the typology of the part, its position and pose for a vision guided part picking. In fact, the cell control system will automatically associate to the part the proper gripping end-effector and generate the picking robot paths.
Robot End-Effectors magazine

A robot End-Effectors magazine is provided to store all the robot end-effectors suited for the dexterous manipulation of the different parts. Its wirings and logics have been developed according to the Z-Fact0r’s innovative control architecture.

Gripping refining

A gripping refining station, equipped with a Renishaw touch probe and linear gauges, has been developed and positioned near the part feeder (to reduce the paths and cycle time). Implementing the Z-REPAIR innovation described in paragraph 5.3, calculates the real exact position of the part relatively to the robot TCP, refining accordingly all the robot programs to improve accuracy and assure an effective and successful repairing action.

Robot

The robot has been positioned in order to have the best accessibility to all the different modules. The robot layout position has been optimized in order to assure its best motion accuracy, measured with the innovation described in paragraph 5.2, which is also exploited to post process all the robot motions and trajectories to improve accuracy and avoid defects during the repairing actions. The robot accuracy “gold zone” cube can be seen in Figure 24; it has been measured for the Robot IRB 2400 1.55m/20kg, that will be used in the demo-cell.
Defect identification
The defect identification innovations, described in paragraph 5.4, have been implemented into a special quality control station, and were positioned in the upper part of the cell, near the feeder, to assure better optical performance and accessibility.

ZD robot intelligent deburring process planner and control systems
The robotic cell control system cabinet, as well as the pneumatic and electrical cabinet, are positioned outside the cell to ease their accessibility during the operations. As previously written, an industrial PC connected with IoT technology, or, optionally, on the cloud, runs the ZD process planner, described in paragraph 5.7, processes the sensory input and generates the optimal sequence of operations, as well as the related control code for each controller. Such process planner validates the code on a digital twin (in Figure 20 it can be seen a screenshot) and should provide the real performance improvement needed to realize a real ZD robotic precision deburring. The Process planner implements the Z-Fact0r’s ZD strategy of paragraph 5.8.

Deburring tools station
All the deburring operations are performed on a multi-tool deburring station, which adopts several SIR custom design spindles as well as the novel intelligent deburring spindle described in paragraph 5.5.
6.3 Experimental validation parts

The innovations developed have been validated mainly on digital prototypes, reducing the experimental validation to the most relevant cases, however the future demonstration will be performed in other Z-Fact0r work packages.

The most promising market, where SIR expects to have a strong industrial impact after the Z-Fact0r project lifetime are the aerospace and high-end automotive sector, nevertheless also a testing on a Z-Fact0r Durit use case, involving machining of green parts, has been investigated.

In any case, to reduce the costs and avoid the problem related with the availability of expensive mechanical parts, as common test case it was chosen an aluminium profile (Figure 25), intentionally cut with defects, other parts were aerospace jet blades and automotive components.

![Figure 25 test-case aluminium profile](image)

For the future demonstration activities a DURIT demo part (Figure 26) was also investigated, with some issues on its fragility, which led to the development of some possible gripping solutions (Figure 27).

![Figure 26 Durit demo part](image)
6.4 Testing, validation and refinement

The testing and validation activities have been performed on each single module and on preliminary workpiece with different level of defects following the Z-Fact0r project ZD strategy (Figure 28), while the complete integration and demonstration will be performed successively in other WPs.
The complete ZD deburring cycle, as well as the tuning of the tools parameters and feed rates, have been performed on both the digital twin and the preliminary demo-cell, providing encouraging results that will be fully assessed during future demonstration activities.
7 Conclusions

A novel concept of intelligent robotic deburring cells, implementing Z-Fact0r’s ZD strategies has been developed, achieving the Innovation 8 and Technical objective TO10 of Z-Fact0r Project.

The extensive use of metrological on-line inspection tools has enabled the iterative evaluation of the product quality at each deburring stage for identifying existing and potential defects. An innovative, digital twin based, robotic deburring process planner processes the sensory input and, thanks to a model based control embedding the knowledge of the deburring process, is able to automatically generate an optimized deburring cycle, choosing the best tools and setting the ideal working parameters. Then, the developed Robot cell supervisory control is finally able to automatically generate the multi-stage deburring cycle at each stage, emulating the adaptability, experience and knowledge of expert human operators. In fact, after each deburring stage, the quality achieved is checked in order to better tune the next operation or, in the worst case, define a proper repairing action.

Proper compliant tools and ZD deburring strategies have been conceived and designed to improve the effectiveness of the repairing actions.

The robust and reliable inference engine developed, based on a digital twin and directly connected with the cell controllers with IoT technology, enables the robotic cell full reconfigurability needed to provide a real online repairing action. A novel control system architecture allows the automatic generation of the robotic cell controllers validated code, adding the robotic cell the “intelligence” to autonomously generate ZD strategy in real-time.

As exploitable results, during the T2.3 the following main enabling innovations have been conceived and developed:

I. A method for assessing the robot motion accuracy to improve the final accuracy of the robot deburring process.

II. A method to post-process robot trajectories and control logics in order to predictively compensate their motion accuracy errors and generate more accurate, first time right robot deburring, avoiding current State-of-the-Art long tuning processes which heavily reduce the overall productivity and costly bring to defects and scraps.

III. A metrology-based solution to detect the real pose of the part to be deburred and a method to refine and calibrate the robot code, in order to eliminate the inevitable accuracy errors occurring when picking the workpiece.

IV. Metrological on-line inspection tools to evaluate product quality at each deburring stage, identifying defects and generating proper triggering messages to the supervisory control which enable the optimizer to develop proper manufacturing sequences and repairing actions.

V. A ZD robotic process planner, which, embedding the knowledge of the deburring process, is able to interpret the robotic cell sensory input and automatically generate an optimized deburring cycle, choosing the best tools and setting the ideal working
parameters. Finally, such optimized deburring cycles are automatically translated into PLC and robot code and sent with IoT technology to the target controllers for an online process reconfiguration and ZD repair.

VI. An object-oriented, IEC-61131 compliant, supervisory control architecture, as well as its integration with parametrized robot control code, which enables the on-line full reconfigurability of the intelligent robotic deburring cell.

VII. A novel architecture for deburring spindles, with online monitoring of the spindle parameters and the compliance status, in order to monitor the process and automatically adapt to unpredicted conditions which would generate further defects.

VIII. A novel architecture of intelligent robotic deburring cells, modular and reconfigurable, for the intelligent precision deburring of high end mechanical parts.

The aforementioned innovations successfully accomplished the technical objectives set in Z-Fact0r’s Innovation 8 (ZD robotic intelligent deburring) as well as Z-Fact0r’s technical objective TO10 (“Develop strategies for product rework to repair defects”).

Nevertheless, such Z-REPAIR fundamental innovations can be configured and engineered also for other Industry 4.0 manufacturing applications, enabling manufacturing systems to be intelligent, cognitive and context aware, being able to generate strategies and self-optimize their behaviour to achieve the ZD manufacturing quality and productivity objectives.

Such innovations will be successively demonstrated and validated at TRL 6.
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