Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 51 (2020) 140–147

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021)
15-18 June 2021, Athens, Greece.

Novel Robotic Cell Architecture for Zero Defect Intelligent Deburring

Juliana Schmidt[a,b]*, Fabio Grandi[a], Margherita Peruzzini[a,c], Roberto Raffaeli[c,d] and Marcello Pellicciari[c,d]

[a]*Dept. of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Vivarelli 10, 41122 Modena, Italy*
[b]*SIR S.P.A., Strada Nazionale del Canaletto Centro, 450, 41122 Modena, Italy*
[c]*Intermech MO.RE., University of Modena and Reggio Emilia, Via Vivarelli 2, 41122 Modena, Italy*
[d]*Dept. of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Via Amendola 2, 42122 Reggio Emilia, Italy*

* Corresponding author. Tel.: +39-0592056278; fax: +39-059-2056129. *E-mail address:* juliana.schmidt@unimore.it

Abstract

Deburring operations are critical to automate when high quality is required, due to the unpredictable presence and variable thickness of burrs that necessitate singular optimized process planning. Industrial anthropomorphic manipulators could effectively perform high quality deburring operations, but still lack the intelligence needed to generate quality and time-optimal deburring cycles. This paper presents a novel architecture of Zero Defect intelligent deburring robotic cells. Vision systems and metrological sensors allow the identification of the burrs and the overall quality and pose of the workpiece, while a novel model-based supervisory control, based on a digital twin, automatically calculates the optimal sequence of operations and working parameters needed to achieve the desired quality, generating also the PLC and robot controllers validated code to perform each task. Finally, the prototype of the proposed Zero Defect intelligent deburring cell has been developed.

Keywords: Zero Defect Manufacturing, Virtual Prototyping, Digital Twin, Engineering methods, Robotic manufacturing, Industry 4.0

1. Introduction

1.1. The deburring process

The deburring of precision mechanical parts is a fundamental process for finishing value-added machined parts to assure the designed performance [1]. Burrs are manufacturing defects that occur on the edges of machined workpieces due to previous process conditions. The presence of such defects is usually unpredictable, and they have variable geometries and thickness. For this reason, deburring operations are generally performed manually by expert human operators, who carefully analyze each workpiece for identifying the burrs and defining which operations are needed, choosing the optimal tools, paths and cutting parameters to achieve the best quality in the shortest time. Furthermore, manual deburring is basically a quality-driven interactive process, in which the operator continuously adapts the tool contact pressure and feedrate for the ideal cutting of each burr, frequently inspecting the quality achieved to tune and refine the next tasks, while always verifying to avoid defects (e.g. cutting too deep). Thus, deburring is a complex multi-tool and multi-stage process in which experienced operators have to plan custom optimal sequence of operations for each single workpiece and tune each task after evaluating the results achieved in the previous one.

Unfortunately, latest generation high value-added mechanical parts have accuracy specifications that often exceed the ones achievable by human operators' deburring, but, at the same time, the cost-effectiveness and productivity of deburring processes must be concurrently improved.

Such performance is achievable adopting automation and robotics, but, as previously explained, to reach the final quality it is necessary to customize the process for each single

10.1016/j.promfg.2020.10.021

workpiece and perform continuous quality monitoring as it was performed by expert human operators.

1.2. Robotic deburring

Much research [2-5] has been carried out to deploy and engineer robotic deburring applications. Currently, last generation of robotic deburring cells are adopted to process low and medium accuracy mechanical parts. Robotic deburring can be distinguished as precision deburring, in which small burrs are removed with cutting tools contouring workpiece machined edges and as heavy deburring, regarding the removal of bigger burrs such as cast flashing. Due to the need of using more tools, cells are usually designed with a "*part-in hand*" configuration (Fig. 1 left), in which the robot manipulates the workpiece and several deburring tools are in fixed positions. With such approach the overall process is carried out faster, due to the minor time needed for using different tools, while the robot can also quickly pick and place different workpieces. When the workpiece is bigger, "*tool in hand*" (Fig. 1 right) configurations are preferred. In this case the robot picks and manipulates the tools.

Fig. 1. "Part in hand" (left) and "tool in hand" (right) robotic deburring cell configuration

In order to standardize the process and avoid the need of human operators, robotic deburring is programmed adopting a "worst case" approach, in which robot trajectories and tasks are conceived to contour all the workpiece edges where possible burrs may occur, while the cutting parameters and feedrate are dimensioned for the thickest burrs. Such robust approach is effective, but it has the drawback to need (much) longer cycle times (and costs), while contouring the edges free of burrs may also lead to excessive cut and overcome the tolerance limits.

Thus, at state-of-the-art, robotic deburring is performed by adopting long, poorly productive cycles in order to be sure to deburr all the edges/surfaces regardless the real presence of the burrs. Nevertheless, the process may lead to defects and scraps. Furthermore, since robots have good repeatability but a limited positional accuracy, long process validation is needed to tune and ramp-up the process, limiting the return on investment and overall operational flexibility of the robotic cell.

The main limitations and source of defects of robotic deburring are namely:

- tool contact and cutting conditions
- robots limited motion accuracy
- workpiece variations and pose accuracy

In particular, the major efforts in the past research have been focused on assuring the optimal contact conditions of the deburring tool with the contouring edges, adapting tool position and stiffness to burr presence and thickness, and avoiding tool breakage in case of unexpected and out of tolerance workpiece geometries. Thus, robotic deburring toolheads or workpiece holders are provided with adaptive compliance, that assures optimal cutting conditions. The main goal is assuring constant tool workpiece contact and pressure despite the workpiece geometry, burrs, and the robot motion positional inaccuracy, to achieve the best accuracy and to avoid chatter. Such adaptive compliance is fundamental and critical for the final robotic deburring performance and operational efficiency.

Two main approaches have been deployed: active and passive compliance [6]. Active compliance solutions are based on advanced hybrid force/position or impedance control strategies [7-12], which require additional force/torque and displacement sensors, and often auxiliary devices and actuators [13-15] to provide adaptive trajectories compensation in response to forces due to geometries variations. The main drawbacks of active compliance solutions are related with the complexity of their development and tuning, embedded in external networked distributed controllers, which in turn often suffer also from the limited bandwidth communication and fast feedback capabilities of industrial robot controllers [16].

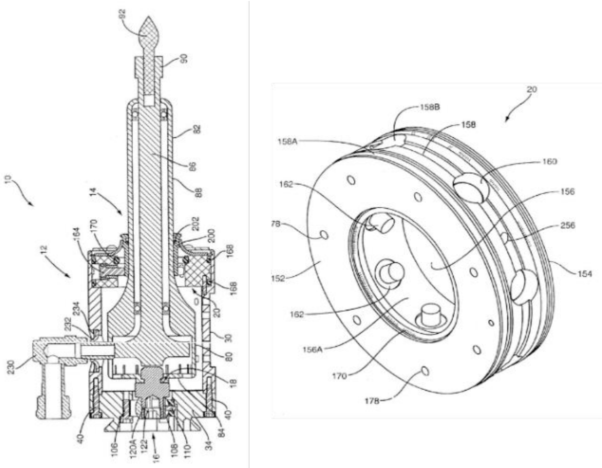

Fig. 2. Radial passive compliant deburring tool (ATI)

Furthermore, the needed auxiliary sensors and actuators impact negatively on the overall costs, and currently active compliant robotic deburring is still limited. However, it must also be noted that active compliance can be programmed and tuned for providing different stiffness compliance and motion laws for different conditions (e.g. burr thickness and geometries and material to be cut), realizing impedance transfer laws and compliance behaviors that cannot be accomplished with passive compliance solutions. Passive compliance solutions are based on passive spring-damper systems, usually adopting mechanical flexural hinges, springs, or pneumatics.

Most designs provide deburring tools specific compliance motion directions, namely axial, planar, or radial [17-21]. In Fig. 2 (adapted from [17]) a widespread robotic deburring compliant tool is shown, in which the radial compliance is provided by a set of pneumatic cylinders radially positioned, which deliver the reaction forces needed to provide the calibrated stiffness.

Robotic deburring passive compliance is usually preferred due to simpler, cheaper, and usually lighter design. Regarding to springs and flexures, pneumatics compliance actuation is mostly adopted, thanks to the ease to fine tune the stiffness, also automatically with proper programmable pneumatic valves. The tuning and optimization of the compliance is a complex and time-consuming process and several studies have accurately modelled the behavior and dynamics of compliant deburring toolheads with virtual prototyping techniques [22-24] for model-based control strategies.

Robots' limited motion accuracy is another major source of error in robot manufacturing applications, leading to paths deviations and overall accuracy errors. Main sources of errors are related with both robot mechanics and controller characteristics [25], namely, robot reducers' friction and backlash, the overall robot's geometry accuracy and the limited controller bandwidth [16, 25-26]. As mentioned before, robotic deburring toolheads' compliance mitigates the effects of such motion accuracy errors but often still lead to defects. Robot kinematic calibration and absolute accuracy methods [27-28] have proved to reduce effectively positional errors, but thermal drifts and process conditions variations are still unsolved. Industrial robots limited motion accuracy has been researched intensively [29-32] also to establish a reliable prediction of the real robotic manufacturing performance with simulation and digital twin. In fact, especially for robotic deburring of precision mechanical parts, production lots batch sizes are continuously shrinking, causing continuous process setup and reconfiguration. Then, offline programming is required to improve profitability and provide the necessary small batch production flexibility.

To this purpose, high-end robot simulation and offline programming tools (e.g. Delmia Robotics®, ABB RobotStudio®, Siemens Process Simulate®) provide deburring and routing wizards that support design engineers in programming complex deburring routines. Even if virtual controllers and Robot Realistic Simulation allow a reliable simulation of the robot controllers real behavior, mechanical accuracy errors sources still persist. Ultra-realistic simulations based on Digital Twins [25] predict machining errors and provide additional predictive path compensations which further reduce such errors, even if long and complex tuning is needed.

Therefore, despite the strong aid of robot simulation and offline programming, new deburring processes still require long manual refining and tuning, wasting several parts and time, thus inhibiting a fully reconfigurable flexible "first time right" production.

Since the random presence and thickness of burrs requires tight tolerances and quality specifications, it is very likely that generic deburring processes could generate unpredictable defects and scraps due to workpiece variations and pose accuracy. Such problem should be solved through a preliminary inspection of the workpiece conditions, in order to identify the burrs presence for planning a custom deburring process for each workpiece with optimal cutting parameters. Finally, the accuracy of the pose of the workpiece is another source of defects that should be taken into account for higher accuracy deburring.

Thus, Zero Defect (ZD) robotic deburring approaches is here devised to provide robots with the intelligence needed to identify the defects (burrs) and develop autonomously custom sequence of operations for repairing them.

2. Zero Defect intelligent robotic deburring process

Automating the deburring of high value-added mechanical parts must cope with important technical and technological challenges, namely i) the improvement of the accuracy of state of the art robot deburring technology, ii) the deployment of a cognitive robotic system, which fully embeds the robotic deburring process knowledge in order to dynamically calculate the optimal process and sequence of operations for each single part, thus mimicking the experience, adaptiveness and flexibility of expert operators, iii) the real time automatic generation, verification and validation of the code for all the target controllers involved (e.g. Robot and PLC).

Such ambitious objectives can be achieved with a Zero Defect (ZD) Manufacturing [33-35] approach, in which quality control is systematically used to identify and analyze the defects for generating the optimal sequence, and the ideal parameters, of the repairing operations. It must be further underlined a fundamental constraint, which is that any solution must be conceived to be compliant with the closed architectures of state-of-the-art robot controllers and PLC supervisors.

The proposed ZD robotic deburring method is here described following its main five stages, namely:

- Nominal Process Planning
- Defects Prediction
- Defects Prevention
- Defects Detection
- Defects Repair

2.1. Nominal process planning

In the nominal process planning, the part to be deburred is accurately evaluated to identify where possible burrs may occur and which is the optimal pose for assuring adequate stiffness and tools reachability. A structured generic nominal deburring process archetype is then developed within a robot simulation and offline environment (e.g. ABB RobotStudio®), including the choice of the set of tools needed for different burr conditions, as well as the range of deburring parameters (e.g. tool offset, feedrate, compliance stiffness). The selection of the tools and deburring parameters is critical, and it still relies on the experience of expert operators and company know how. The process is segmented and structured in composable standalone self-contained modules; each module is referred to specific portions of contouring edges in which the manufacturing engineers know that possibly burrs may occur, parametrizing it (e.g. cutting offset, compliance stiffness, feedrate..) in function of the entity of the burrs. In this way it is possible to configure online a custom deburring process for each single workpiece, choosing to deburr only the contouring edges in which burrs are really present; furthermore, once the burrs are identified and detected, proper deburring parameters, consistent with the burrs thickness and geometry detected on the real workpiece, will be assigned in order to assure optimal tool contact and cutting conditions. Such approach allows the modular customization of the deburring cycle for each piece condition, configuring the sequence of operations by composing the modules and specific parameters according to the defective contouring edges.

2.2. Defects prediction and prevention

Once the configurable robotic nominal deburring process has been developed, robot trajectories are verified and validated in the robot simulation digital environment, with a special focus on identifying robot motion accuracy errors that may cause loss of accuracy performance, namely backlash, motion profiles and tool engagement. Such "defects prediction" analysis is performed on the joint space, evaluating each actuator motion profile, in order to predict the occurrence of defects due to the limited motion accuracy of the robot. The detection of possible motion accuracy errors enables the generation of compensated trajectories, deployed by the elimination of the errors due to backlash and lost motions. Such "defects prevention" approach, originally conceived in [25, 36], allows to prevent possible defects by predictive compensation, and in previous research projects [25] it has proved to successfully improve machining robotic processes. Deburring defects prediction and prevention is fundamental for achieving a first time right ZD robotic deburring, that otherwise would require long tuning and validation. Thus, in order to mimic the deburring practice of expert human operators, the proposed approach executes quality control before the deburring operations, identifying the burrs to allow an optimized process planning focused on eliminating such defects only, and perform it in real time with a "first-time-right" approach. Then, ZD manufacturing approaches leverage quality controls not only for the verification of the quality achieved, but especially for the generation of optimized defect repairing actions, conceived, and developed by advanced simulation and artificial intelligence.

The proposed ZD robotic deburring method (Fig. 3) is organized in an offline accurate planning, based on a digital twin embedding the deburring process knowledge of a generic part, and an online monitoring and control part, in which robots are able to implement the ZD strategy by reacting in real time to deviations and errors.

2.3. Defects detection

It is important to emphasize that the proposed ZD manufacturing approach leverages quality control as inference engine for planning custom repairing processes, optimized to achieve the desired quality by repairing the sensed defects and preventing the potentially incurring defects due to the workpiece conditions, instead of providing just a feedback of previous operations. Such proactive approach is fundamental to cope with the inevitable heavy and random process variations

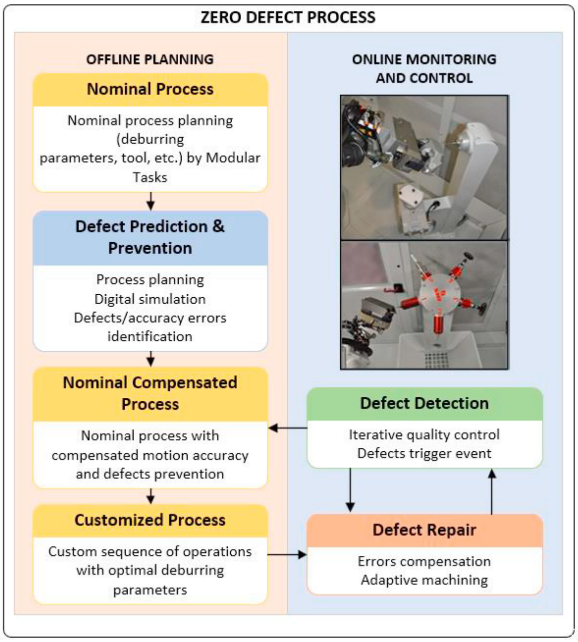

Fig. 3. Zero Defect robotic deburring process

that deburring must solve. Unlike the state-of-the-art robotic deburring automation, following this approach each process is unique and customized for the singular workpiece, realizing only the value-added operations with optimal parameters.

Quality control is then systematically performed to detect occurred defects but also to identify critical conditions that could lead to the generation of new defects. Defects (occurred or potentially incoming) detection is then crucial for implementing an effective ZD robotic deburring. It enables effective adaptations and repairing actions, thus in a ZD deburring cell quality controls are performed more frequently and systematically. However, the additional time needed for such quality controls does not generally lead to an increase of the final cycle time. On the contrary, since the robotic system is provided with the intelligence for defining the optimal sequence of operations needed, it can avoid performing many lengthy unnecessary operations that otherwise should be carried out but without adding value. Such quality controls should be performed with vision systems or laser probes (i.e. non-contact), while the results of each control should be recorded and sent to an external server for statistical analysis.

Another source of defects that must be mandatory detected is related with the workpiece pose errors that usually occur during the gripping of the part. To this purpose, once the workpiece has been clamped by the robot, its pose is evaluated, sensing several machined datums and comparing them with the robot Tool Center Point (TCP). The measurements can be performed with optical sensors (e.g. laser displacement sensors) or a touch probe metrological station (Fig. 4), while custom algorithms (which will be discussed in future works) calculate the real pose of the workpiece respect the robot TCP evaluating also the inevitable accuracy sensing errors, including the robot positional accuracy drift.

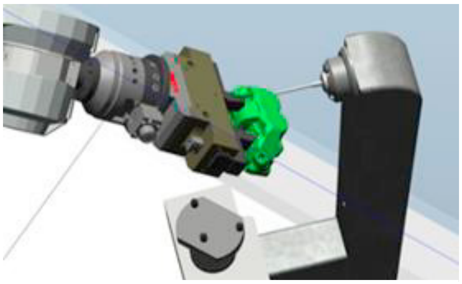

Fig. 4. Pose compensation with touch probe

2.4. Defects Repair

Finally, once the quality control is performed and defects have been detected, an inferential process planner, based on digital twin, can quickly calculate the optimal sequence of operations in order to strictly deburr only the edges where burrs have been detected. As previously explained, this task is performed exploiting the availability of a modular and parametrized nominal process archetype, tuned, and validated on a digital twin. Thus, the process planner, having in input the quality control results, automatically composes the sequence of operations, assigning the proper deburring parameters, adding robot tool "approaches" and "exits" for each contour and generating the target controllers code after the verification and validation of the motions and trajectories. The availability of a validated nominal process archetype is fundamental for the online generation and execution of the custom ZD deburring process, that otherwise should require long and time-consuming verification and validation, with the supervision of expert process engineers. The automatic code generation is another challenge to solve, already addressed in previous works [37-39], especially because in this case it must be generated for the multiple target controllers involved (at least the robot controller and the cell PLC supervisor on state of the art robotic cells). Such constraints require to integrate the design of an object-oriented software structure with a consequent input / output (I/Os) signals and electrical cabling hierarchical structure, in order to decouple the PLC and robot controller signals and ease the generation of the different operations code. Thus, the proposed ZD intelligent robotic deburring process must be implemented by a cyber physical production system in which all the tasks and actions are autonomously generated live after cognitively sensing the workpiece quality and monitoring the effects of the deburring process. In particular, the proposed intelligent manufacturing process (Fig. 5) is based on the continuous iteration of quality control tasks for defects detection, the subsequent generation of actionable repairing (deburring) operations, the automatic related code generation and their execution, and, at the end of each deburring stage, a further quality control to verify the accomplishment of the desired quality. Of course, in the case that the quality requirements have not been achieved, further process iteration would be executed. All the data related with the process can be recorded and stored externally for further analysis.

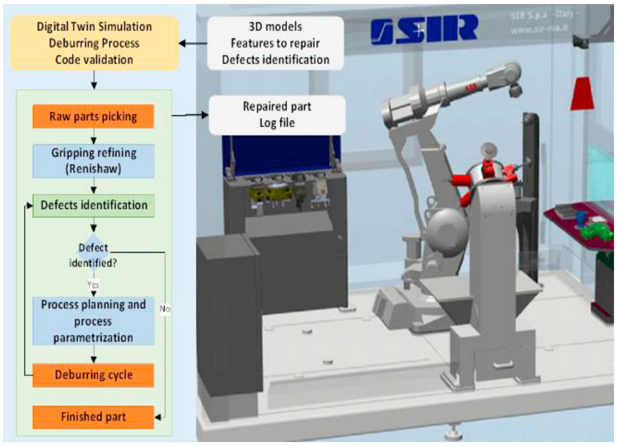

Fig. 5. ZD intelligent robotic deburring iterative process

3. ZD intelligent Robotic deburring cell architecture

The robotic cell architecture is developed following the proposed ZD intelligent robotic deburring process structure, adopting a mechatronic engineering design approach, and focusing on modularity in order to configure custom cells for specific applications and customer requirements.

Thus, the process workflow, as shown in Fig. 5, leads to the definition of the main physical functional modules of the robotic cell, namely:

- Parts feeding and sorting
- Part manipulation end-effectors
- Parts pose accuracy compensation
- Burrs detection
- Deburring

Each module has a hardware-independent signals and software structure, as well as a standard mechanical interface.

The modular design allows to configure each functional module with physical solutions according to customer needs,

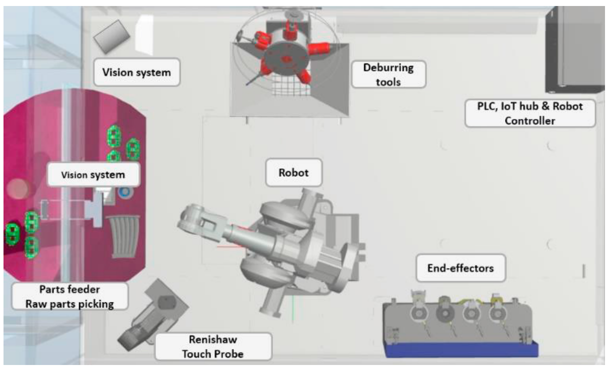

Fig. 6. CAD model of the ZD intelligent robotic deburring

requirements and budget. Fig. 6 depicts the 3D CAD model of the cell, where all the modules are clearly identified.

A demonstration prototype of the aforementioned ZD intelligent deburring robotic cell has been designed in detail and built for experimental validation.

3.1. Parts feeding and sorting

Parts feeding has a dedicated area. A rotational turning table has been chosen as main solution for the module, due to its proven reliability and robustness in securely separating the feeding area from the robot cell. For mass production purposes, the parts can be positioned on a pallet in fixed positions on custom jigs, reducing the costs and allowing a fast and precise picking. Otherwise, in case of flexible mixed and variable production, parts can be positioned randomly on the table. In this latter case, as shown in Fig. 6 a vision system sorts and identifies each single part, and communicates the supervisory PLC the information of the part and its pose, which in turn will associate the proper end effector to use and generate the set points for the robot picking.

3.2. Part manipulation end-effectors

The manipulation of the parts for deburring operations must be performed with elevated dexterity in order to assure the best cutting tool accessibility during the complex deburring motions. To this purpose a set of grippers end-effectors has been designed, for different parts and poses.

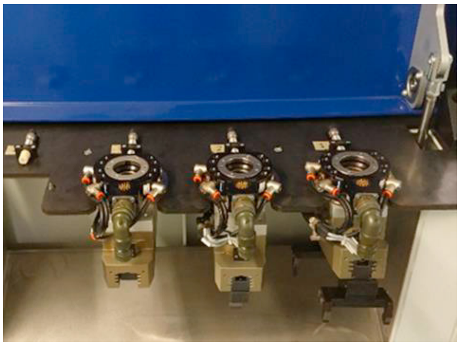

Fig. 7. Gripping end-effectors magazine

Such gripping end-effectors are stored in a magazine (Fig. 7), where the robot can pick the proper end of arm tooling for each part thanks to a quick-change device common interface. In the prototype cell a 4 end-effector tooling magazine has been realized. The parametric module has been designed to be configured for up to 6 end-effectors.

3.3. Parts pose accuracy compensation

Once the workpiece has been picked its pose accuracy is verified in a refining station, shown in Fig. 8. A metrological sensor (a touch probe or displacement sensor, depending on the cell configurations) measures the position of workpiece datums and compares them with the robot end effector, in order to compensate the inevitable gripping accuracy errors, the algorithms and pre-setting strategies will be discussed in future works. Then the robot code is recalibrated with the correct pose of the workpiece. In case multiple gripping poses are necessary to provide an adequate accessibility, a pneumatic indexer allows to place the workpiece and pick it on the opposite side.

Fig. 8. Refining station

3.4. Burrs detection

Several quality control and defect detection modules have been developed and can be chosen to detect defects, namely the inevitable pose accuracy errors that occur during the gripping of the workpiece and the detection of presence and consistence of burrs. A basic refining station can be configured choosing between contact and non-contact sensors, the standard solution being a metrological touch probe able to measure and calculate the displacement of the workpiece respect the robot TCP. Such touch probe has been chosen for the prototype robotic cell (Fig. 8). A hardware-independent common software interface allows the seamless adoption of different sensors without the need to write new instructions, in particular, alternative solutions can be optical sensors (e.g. laser displacement sensors); such approach is fundamental for quality control modules, since it happens that for each industrial case different sensors technology show unexpected performance, then it is vital to have the possibility to configure between different sensors. The same approach has been adopted for the burrs detection, in this case non-contact sensing is preferred, especially for flashing and small burrs. 3D scanners have been tested and provided good performance, but the main solution is based on a vision system. For the robotic cell prototype a Smartek GCC414 camera has been chosen, and the burrs detection algorithms have been developed with the Halcon machine vision library.

3.5. Deburring

Precision deburring is a complex and sensitive process, it is then fundamental to adopt proper tooling for achieving the best performance. To this purpose, a mix of combination of spindles and tools have been tested and validated. A family of parametric deburring spindles has been designed with different selective compliance solutions (e.g. radial, planar, angular, axial...), each pneumatic spindle can be chosen with different operating speed for specific materials and tools. A five tools deburring station has been designed (Fig. 9), the 5 spindles are equally spaced on a cylindrical rotary base, in order to provide the necessary accessibility. Regarding previously developed solutions, where the multi-tool deburring station base can place the spindles in fixed positions due to a cam indexer, the proposed design uses a zero-backlash compact harmonic drive servo-actuator in order

Fig. 9. Multi spindle deburring station

to position each spindle in the most suitable place, or even interpolate with the robot as seventh axis, with a task time of 12ms.

The spindle passive selective compliance is provided pneumatically, and different levels of stiffness can be set by assigning different pressure values.

4. Conclusions

The research presents a new architecture for intelligent deburring cells. The modularity and reconfigurability of this solution allow the flexibility of manufacturing processes, which is crucial for the current industrial context. A novel model-based supervisory control exploits quality control to identify defects for autonomously developing optimized tailored deburring cycles. The defects are then repaired, and the quality of the worked component is verified in a continuous monitoring process. The proposed approach improves also the accuracy performance of robotic deburring. Simulations carried out in the virtual environment allow to predictively compensate for precision errors, generating a more accurate and first-time-right deburring process.

The metrological control of the workpiece quality allows the detection of defects during each stage of the process. This process feedback allows the generation of custom deburring cycles, tailored for the unique needs of the single workpiece. The extensive adoption of quality control tasks with a novel proactive approach finally enables the implementation of flexible automation and intelligent manufacturing approach, where cognitive robots are able to autonomously generate optimal strategies to achieve the desired quality performing only value added tasks. The strength of this solution is supported by the knowledge embedded in the model-based control. The iterative quality check and the constant adaptation of the process to specific conditions can be compared to simulate actions carried out by expert human operators.

The implementation of the presented intelligent robotic deburring cell seems to be promising, proposed to be addressed in future works. Specific innovations will be presented, and the experimental results of the prototype cell will be discussed.

Acknowledgements

The research leading to this paper is supported by European Union’s Horizon 2020 research and innovation program under grant agreement No. 723906, project Z-Fact0r.

References

[1] Ahmad MM, Sullivan WG. Flexible automation and intelligent manufacturing 2001. Robotics and Computer-Integrated Manufacturing. 2002;18(3-4):169-70.

[2] Chen Y, Dong F. Robot machining: recent development and future research issues. The International Journal of Advanced Manufacturing Technology. 2013 Jun 1;66(9-12):1489-97.

[3] Ryuh BS, Pennock GR. Robot automation systems for deburring. InIndustrial Robotics: Programming, Simulation and Applications 2006 Dec 1. IntechOpen.

[4] Morris C. Robots for deburring. Advanced Manufacturing Technology. 2012 Nov 15;33(11):6-8.

[5] Ryuh BS, Pennock GR. Robot automation systems for deburring. InIndustrial Robotics: Programming, Simulation and Applications 2006 Dec 1. IntechOpen.

[6] Odham A. Active and Passive Force Control Robotic Deburring. RIA Grinding, Deburring and Finishing Workshop 2007.

[7] Mendes N, Neto P, Pires JN, Moreira AP. Fuzzy-PI force control for industrial robotics. FIRA RoboWorld Congress 2010 Sep 15 (pp. 322-329). Springer, Berlin, Heidelberg.

[8] Ma Z, Hong GS, Ang MH, Poo AN, Lin W. A Force Control Method with Positive Feedback for Industrial Finishing Applications. 2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) 2018 Jul 9 (pp. 810-815). IEEE.

[9] Mendes N, Neto P, Pires JN, Loureiro A. An optimal fuzzy-PI force/motion controller to increase industrial robot autonomy. The International Journal of Advanced Manufacturing Technology. 2013 Sep 1;68(1-4):435-41.

[10] Kuss A, Drust M, Verl A. Detection of workpiece shape deviations for tool path adaptation in robotic deburring systems. Procedia CIRP. 2016 Jan 1;57:545-50.

[11] Franks J, Pan Z, Zhang H. Robotic machining from programming to process control: a complete solution by force control. Industrial Robot: An International Journal. 2008 Aug 22.

[12] Beck J, Sencer B, Balasubramanian R, Meader J. Design of a flexure-based active fixture system for precision robotic deburring. ASME 2018 13th International Manufacturing Science and Engineering Conference 2018 Jun 18. American Society of Mechanical Engineers Digital Collection.

[13] Lopes A, Almeida F. A force–impedance controlled industrial robot using an active robotic auxiliary device. Robotics and Computer-Integrated Manufacturing. 2008 Jun 1;24(3):299-309.

[14] Olofsson B, Sörnmo O, Schneider U, Robertsson A, Puzik A, Johansson R. Modeling and control of a piezo-actuated high-dynamic compensation mechanism for industrial robots. 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems 2011 Sep 25 (pp. 4704-4709). IEEE.

[15] Burghardt A, Szybicki D, Kurc K, Muszyńska M. Optimization of process parameters of edge robotic deburring with force control. International Journal of Applied Mechanics and Engineering. 2016 Dec 1;21(4):987-95.

[16] Pan Z, Zhang H, Zhu Z, Wang J. Chatter analysis of robotic machining process. Journal of materials processing technology. 2006 Apr 20;173(3):301-9.

[17] Lawson DK, inventor; ATI Industrial Automation Inc, assignee. Deburring tool. United States patent US 6,974,286. 2005 Dec 13.

[18] Passoni L, inventor; SIR S.P.A. Spindle for putting into rotation of tools, particularly for finishing operations or similar patent ITMO20060107A1

[19] Passoni L, inventor; SIR S.P.A. Station for mechanical machining of parts comprising a robotic arm. European patent EP1905537B1. 2011 Jun 8.

[20] Sweet T, Lawson DK, inventors; ATI Industrial Automation Inc, assignee. Axially and radially compliant deburring tool. United States patent application US 15/705,658. 2019 Mar 21.

[21] Chen J, Jiang F, Xu Y, Li S. Design and Analysis of a Compliant Parallel Polishing Toolhead. International Conference on Mechanical Design 2017 Oct 13 (pp. 1291-1307). Springer, Singapore.

[22] Berselli G, Pellicciari M, Bigi G, Razzoli RP. Design optimisation of cutting parameters for a class of radially-compliant spindles via virtual prototyping tools. International Journal of Computer Aided Engineering and Technology. 2019;11(2):232-52.
[23] Schützer K, Abele E, Güth S. Simulation-based deburring tool and process development. CIRP Annals. 2015 Jan 1;64(1):357-60.
[24] Liao L, Xi FJ, Liu K. Modeling and control of automated polishing/deburring process using a dual-purpose compliant toolhead. International Journal of Machine Tools and Manufacture. 2008 Oct 1;48(12-13):1454-63.
[25] Lehmann C, Pellicciari M, Drust M, Gunnink JW. Machining with industrial robots: the COMET project approach. InInternational Workshop on Robotics in Smart Manufacturing 2013 Jun 26 (pp. 27-36). Springer, Berlin, Heidelberg.
[26] Kluz R, Trzepieciński T. The repeatability positioning analysis of the industrial robot arm. Assembly Automation. 2014 Jul 29; 34 (3): 285–295.
[27] Hollerbach J J. A Review of Kinematic Calibration. The Robotic Review 1, Khatib, O., J.J. Craig and T. Lozanol-Perez (Eds.). MIT Press, Cambridge, MA., 1989, pp: 207-242
[28] Conrad KL, Shiakolas PS, Yih TC. Robotic calibration issues: Accuracy, repeatability and calibration. InProceedings of the 8th Mediterranean Conference on Control and Automation (MED2000), Rio, Patras, Greece 2000 Jul 17 (Vol. 1719).
[29] Cristalli C, Boria S, Massa D, Lattanzi L, Concettoni E. A Cyber-Physical System approach for the design of a modular Smart Robotic Cell. IECON 2016-42nd Annual Conference of the IEEE Industrial Electronics Society 2016 Oct 23 (pp. 4845-4850). IEEE.
[30] Lehmann C, Halbauer M, van der Zwaag J, Schneider U, Berger U. Offline path compensation to improve accuracy of industrial robots for machining applications. Proc. of 14th Automation Congress, Baden-Baden, Germany 2013.
[31] Bennett DJ, Hollerbach JM, Henri PD. Kinematic calibration by direct estimation of the Jacobian matrix. Proceedings 1992 IEEE International Conference on Robotics and Automation 1992 May 12 (pp. 351-357). IEEE.
[32] Schneider U, Drust M, Ansaloni M et al. Improving robotic machining accuracy through experimental error investigation and modular compensation. The International Journal of Advanced Manufacturing Technology. 2016 Jul 1;85(1-4):3-15.
[33] Foche G. A guide to Zero Defects, Quality and Reliability Assurance Handbook. Office of the assistant secretary of defence, US., Washington. 1965.
[34] Westkämper E, Warnecke HJ. Zero-defect manufacturing by means of a learning supervision of process chains. CIRP annals. 1994 Jan 1;43(1):405-8.
[35] Psarommatis F, Kiritsis D. A scheduling tool for achieving zero defect manufacturing (ZDM): a conceptual framework. IFIP International Conference on Advances in Production Management Systems 2018 Aug 26 (pp. 271-278). Springer, Cham.
[36] Pellicciari M, Berselli G, Balugani F, Gadaleta M. Increasing position accuracy and energy efficiency of servo-actuated mechanisms. 2015 IEEE International Conference on Automation Science and Engineering (CASE) 2015 Aug 24 (pp. 1339-1344). IEEE.
[37] Estévez E, García AS, García JG, Ortega JG. ART2ool: a model-driven framework to generate target code for robot handling tasks. The International Journal of Advanced Manufacturing Technology. 2018 Jul 1;97(1-4):1195-207.
[38] Gadaleta M, Pellicciari M, Berselli G. Optimization of the energy consumption of industrial robots for automatic code generation. Robotics and Computer-Integrated Manufacturing. 2019 Jun 1;57:452-64.
[39] Gleeson D, Björkenstam S, Bohlin R, Carlson JS, Lennartson B. Towards Energy optimization using trajectory smoothing and automatic code generation for robotic assembly. Procedia CIRP. 2016 Jan 1;44:341-6.