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Human-robot collaborative reconfigurable platform for surface finishing processes

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Abstract

Surface polishing can be counted among the most challenging manufacturing operations, especially when high qualitative levels in terms of surface texture characteristics are requested, such as in the case of polishing operations for plastic injection moulds. Robot-based solutions for surface polishing and quality assessment operations have been proposed at the state of the art, but it still is required the involvement of skilled workers for process supervision and final tuning operations. The introduction of human-machine collaborative solutions opens new opportunities, as the use of symbiotic polishing approaches, where both the humans and the machines capabilities can be shared to improve process effectiveness. The current work proposes a human-robot collaborative approach for surface polishing processes that integrates state of the art robot-based polishing and surface quality assessment technologies in a human-safe shared working environment. As a proof of approach feasibility, the paper presents the prototype of a reconfigurable platform designed to implement a flexible human-robot collaborative scenario for execution of polishing and quality assessment operations. Preliminary demonstrative polishing sessions on simple and complex components validate the system effectiveness with respect to manufacturing efficiency and reconfigurability capabilities. The results obtained provide a first positive response that symbiotic approach can objectively improve the polishing processes.

Keywords: Collaborative Robotics; Polishing Processes; Reconfigurable Systems; Robotics and Computer Integrated Manufacturing

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1. Introduction

In today's manufacturing industry, the surface finishing represents a challenging process since it requests the repetition of subsequent operations which gradually and carefully remove an increasingly smaller amount of material until the expected surface quality is reached. Consequently, the automation of this process is limited to simple components, as in the case of engine, hydraulics, transmissions parts that require high surface finishing [1–5]. On the other hand, manual approaches are still widely used especially for the finishing of complex surfaces, such as those related to big moulds used in the automotive industry for the production of plastic injection moulded parts. For these cases, the manual finishing is performed using dedicated tools and abrasive media shaped accordingly to surfaces to polish. The parameter driving the subsequent operations is the abrasive capacity of the media, since its value is directly connected to the maximum amount of material removed. Consequently, the initial operations make use of high abrasion media, while the last operations require low abrasion media. Furthermore, the approach guiding the application of the abrasive media is important in order to avoid defects, such as changes in surface shapes and scratches. The detection of the proper abrasive media as well as the recognition of surface defects is strictly related to the polisher's skills, which is request to evaluate the surface quality with his/her senses while executing the polishing operations. In order to propose effective automatic approaches, many researches focus on designing and testing Robot Assisted Polishing (RAP) solutions, which exploit inherent flexibility and dexterity owned by industrial robots joined to dedicated end-effectors designed for finishing processes, following the conceptual representation of automated die and mould polishing proposed by [6]. A semi-automatic RAP machine based on the coordinated use of an industrial robot and rotational chuck has been evaluated in [7]. The robot mounts a dedicated polishing module that brings the polishing tool in contact to the surface of 2D rotationally symmetric objects rotated by the chuck. The concept has been further extended by [8], which focuses on developing and testing a pneumatic air-compensated robot end-effector dedicated to high finishing operation of complex surfaces. Further improvements by the same Authors have been presented in [9], where the polishing parameter driving the abrasive finishing are managed by offline programming (OLP) software that generate the polishing paths. In parallel to abrasive finishing techniques, fluid-jet abrasive approaches have been also proposed. Again, the solution proposed in [10] extends the use of available fluid-jet systems toward the material removal rates required to perform finest polishing operations. In addition to abrasive technologies, other researches focus on surface quality assessment approaches for automated solutions [11]. A relation between surface roughness and acoustic emission signals is proposed in [12]. A multi-sensory approach that merges acoustic, frictions forces and areal surface parameters has been proposed in [13] for on-line detections of process end point and the surface quality, subsequently further investigated by the same Authors in [14, 15]. The areal parameters are assumed as an objective and univocal key-indicators of the surface quality. Consequently, industrial solutions for online optical assessment have been proposed as a support of RAP, as in the case of structured-light systems. A good example is the CWS system developed by QISAB AB, which allows contact-less measuring of technical surfaces directly in harsh production environments, and its flexible integration as a dedicated end-effector for industrial robots [16]. The collection of references here provided demonstrates how deep it is the research activity developing robot-based autonomous solutions for polishing processes. Nevertheless, it is not still present a reference solution which effectively integrate the available technologies for RAP. The present work presents a novel solution for automated polishing processes which symbiotically combines the RAP technologies with human skills. The solution proposed is the result of a join research experience within the European project SYMPLEXITY, which outlined the emerging needs with regards to automated solutions for finishing processes [17]. Therefore, the subsequent *Section 2* describes the reference approach. The *Section 3* provides a detailed description of the integrated human robot collaborative prototype solution for polishing processes while its experimental evaluation is presented in subsequent *Section 4*. Finally, the *Section 5* provides some conclusive remarks and the potential future developments.

2. Human-robot collaborative approach for flexible polishing processes

The proposed novel solution for automated polishing processes aims to combine the technologies available at the state of the art and the potentialities of Human-Robot Collaboration (HRC) to drive the development of novel integrated polishing solutions. The founding idea is the same that leads to the development of the HRC solutions: the robots execute repetitive, simple, long and burdensome operations, while the skilled operators perform high valueadded operations that require the high sensitivity, high dexterity and adaptation capacity intrinsically possessed by humans [18]. Furthermore, the polishing technologies are integrated to provide complementary capabilities in terms of the reachable surface quality. The approach has been sketched previously in [19, 20], but here is deeply detailed following the work-flow shown in Fig. 1.

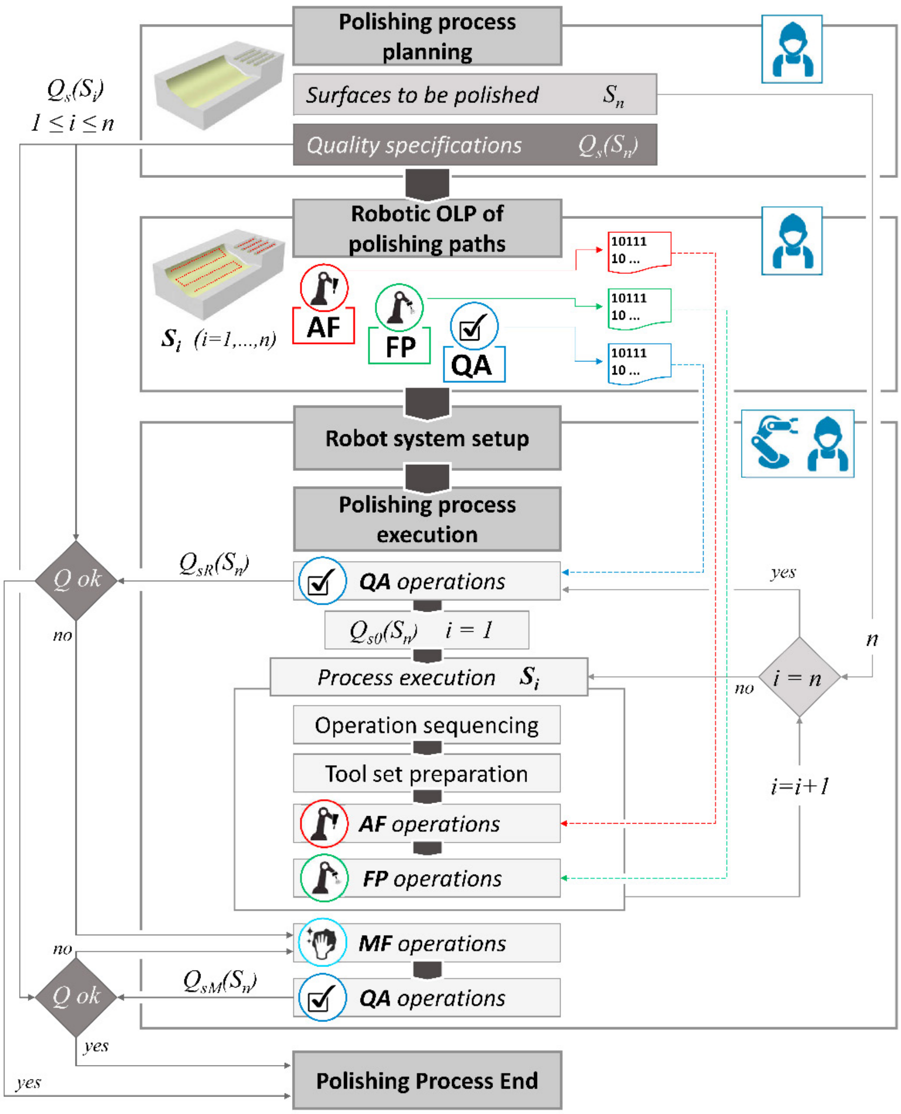

Fig. 1. Conceptual representation of human robot collaborative approach for a surface finishing reconfigurable robotic processes.

The HRC for surface polishing operations is driven by the two initial phases of *Polishing process planning* and *Robotic OLP of polishing paths*. The former identifies the surfaces to be polished, S_n, and the specifications for the quality expected on the selected surfaces, $Q_s(S_n)$. The latter is a computing phase that returns the robot paths to execute the polishing and quality assessment operations on the selected surfaces according to the working approach related to selected robotic tools. Three main types of operations could be identified: *Abrasive Finishing* - *AF*; *FluidJet Polishing* - *FP*; *Quality Assessment* - *QA*. Both the two phases are human-driven and require deep knowledge on both the polishing process and robot polishing approach to provide the quality specifications of the selected surfaces and the requested robot codes. Subsequently human and robot collaboration is expected to perform foreseen polishing operations. The *Robot system setup* is a collaborative phase where the operator places and fixes the workpiece and arranges the requested polishing tools while the robot starts the calibration process to align the programmed paths with respect to the position of the real surfaces and the calibration of the tools [21, 22]. The required operations are selected by the operator through a dedicated interface which feeds the robot with codes of programmed paths following the sequence imposed by the user. The *Polishing process execution* phase starts with quality assessment operations to measure the initial state of the surfaces to be polished, $Q_{s0}(S_n)$. *QA* operations are suitable HRC scenario; conversely, the following operations of *AF* or *FP* require to isolate the robot in a closed environment where the human cannot enter while the tools are active. At the end of the robot processes, a *QA* session is performed again to measure the quality reached by the robotic processes, $Q_{sR}(S_n)$. If some surfaces do not meet the expected quality specifications, the operator performs *Manual Finishing* - *MF* operations until the quality reached by the manual finishing stage, $Q_{sM}(S_n)$, will achieve the expected values. The *MF* is a collaborative stage where human and robot can share the working space.

3. Experimental HRC reconfigurable platform

The previously described approach has been followed to design the experimental prototype of HRC reconfigurable platform that integrates known abrasive finishing technologies in the same working environment, which is shared between an operator and a robot. The solution has been used as a demonstrative workcell for the European project SYMPLEXITY [17] and an overview of the results is presented in Fig. 2, where external and internal views of the whole robot workcell are respectively depicted on the left and the right side. The reconfigurable architecture of the robot cell results from the design of operations-dependent system modules, which can be easily replaced (by the robot itself or by the operator) with respect to the required finishing process. Moreover, the reconfigurability has been also designed to easily change the cell environment to deny or allow the user to enter the robot working space respectively for the un-collaborative and collaborative operations. In details the reconfigurable workcell contains an industrial robot, which is an IRB 4600 ABB robotic arm with 60kg payload, a working area where to place the components to polish and storage areas where to park end-effectors and tools.

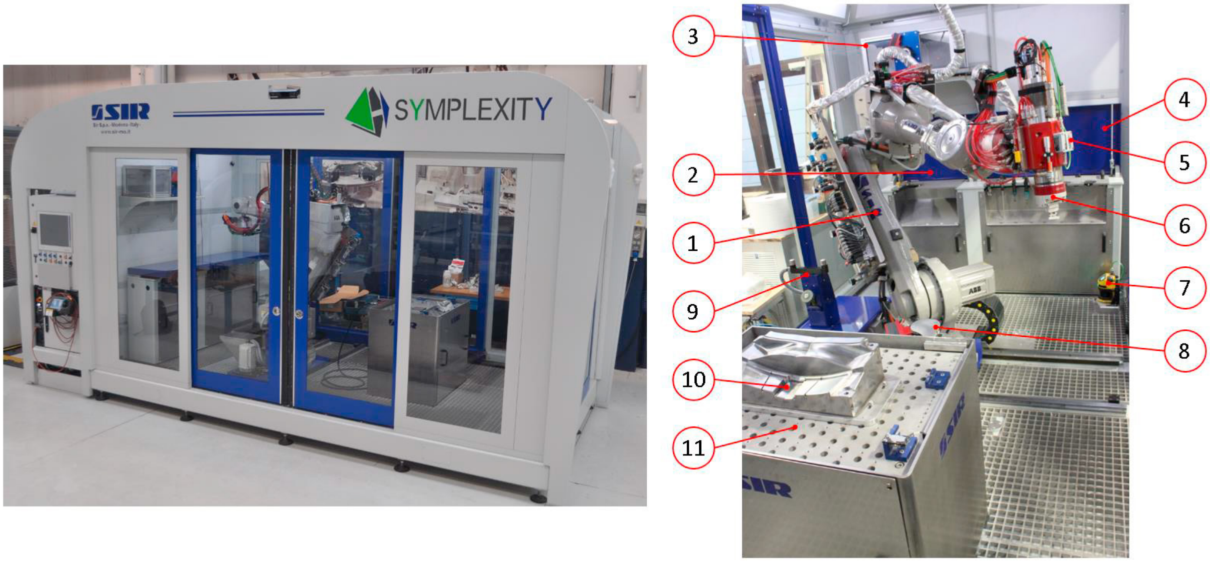

Fig. 2. On the left side, external view of reconfigurable human-robot collaborative workcell for polishing processes. On the right side, the internal elements and related numbered call-out balloons: the robot (1); the storages units for AF spindle (2), FP protective box (3) and AF tool holders (4); AF spindle (5); tool holders for AF attached to spindle (6); one of the two safety laser scanners (7); parking zone for FP lance (8); dressing and measuring unit for AF tool (9); workpiece (10); working table (11).

By means of a common interface placed on the robot terminal flange, the solution can manage three types of end-effector: an electrical spindle for AF; a polishing lance for FJ; the CWS for QA. Moreover, the electrical spindle can in turn exchange AF tool holders and calibration probe. Abrasive capacity of the tools is controlled by the robot on a dedicated unit where to reshape/redress the tool end-point and to measure its length. Consequently, the reconfigurable platform systematically manages the standalone robot-assisted polishing solutions proposed by [9–11] and described in *Section 1*. Inside the workcell cabin, the HRC is possible thanks to a safety architecture that integrates a novel coexistence approach based on Kinect sensors with industrial certified safety technologies managed by a safety PLC [20]. The user and workcell interaction is possible through a dedicate HMI that allows to reconfigure the cell with respect to selected process. The upstream operations to offline programming the polishing paths are possible thanks to a digital twin of the workcell that has been recreated with PowerMill Robot, the OLP software tool selected and customized for the polishing operations [23]. The right side of Fig. 2 depicts the internal view of robot workcell to point out the core elements, numbered from 1 to 11 as follows: robot; storages units for AF spindle, FP protective box and AF tool holders; AF spindle; tool holders for AF attached to spindle; one of the two safety laser scanners; parking zone for FP lance; dressing and measuring unit for AF tool; workpiece; working table.

4. Results and their validation

To validate effectiveness of HRC reconfigurable platform in terms of manufacturing efficiency and reconfigurability with respect to the fully manual or robot-based polishing approaches, preliminarily polishing processes have been performed with respect to demonstrative parts. Specific tests were executed on simple flat sample plates; subsequently, a whole HRC polishing process have been tested on a demo mould. The material used for plates and demo mould was pre-hardened steel, type 1.2738, which is typically used to realize moulds for injection plastic processes. The initial state of surfaces was achieved by the same milling process used to machine the mould. The 3D models of plates and demo mould have been used to offline programming the processes paths for the robot. Thanks to a calibration operation, the origin of 3D model is aligned to the real parts and the offine programmed paths are shifted on the real surfaces. Fig. 3 provides the experimental stages with respect to flat sample plates, from the offline programming of processes paths up to the execution of QA, AF and FP, through the calibration operation that is the same for all the operations related to same part. The QA operations return quantitative data maps that prove the effective improvement of the surface quality. Moreover, these maps show the zones that need further improvements. Consequently, the polisher can launch the robot polishing or directly execute manual finishing operations only on the surfaces where the quality does not reach the expected specification.

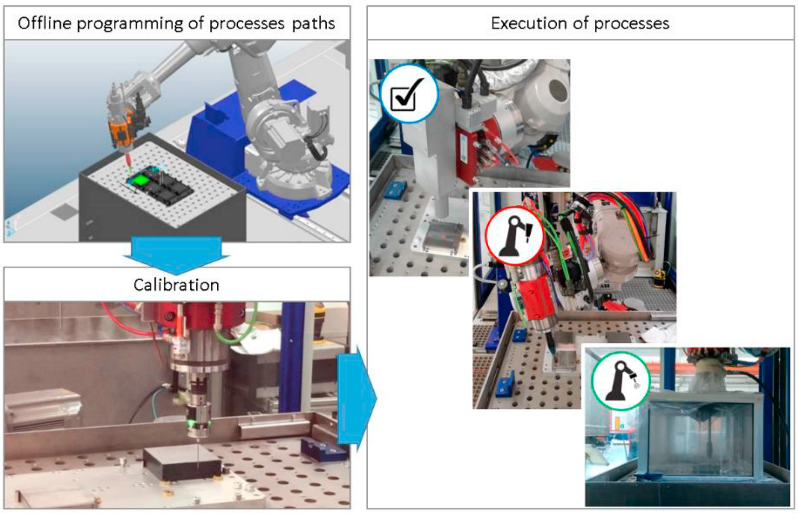

Fig. 3. Experimental stages for the flat sample plates.

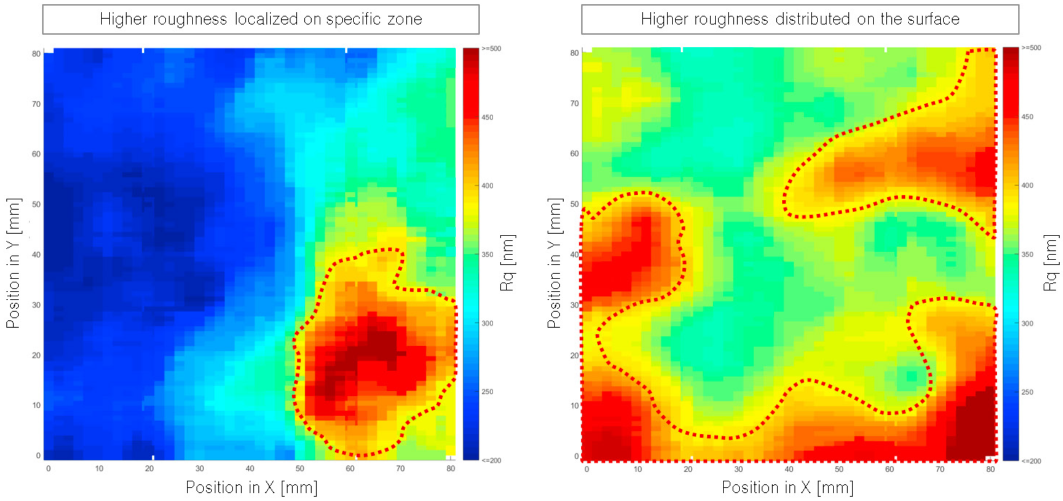

Fig. 4. Color maps for *Rq* parameter. On the left, the case of a localized zone with *Rq* greater than the specified value. On the right, the case where a too high and not constant *Rq* is distributed on the surface.

A good example of the output returned by the HMI is shown in Fig. 4, which shows the colors maps of two flat sample plates for the parameter *Rq* expressed in *nanometers*, nm, returned by the CWS system. This parameter is directly proportional to the surface root mean square (RMS) roughness value and is also noted as Rq_{eq}, equivalent to the *Rq* from ISO 25178-2 [16, 24]. Assuming the reference value of 0.3 nm for *Rq*, the color maps help the polisher with the subsequent operations. With respect to color map on the left side of Fig. 4, it is possible to recognize a restricted not-compliant area placed on the bottom right corner of the measured surface, within a red dotted outline. Consequently, the polisher can easily concentrate the refining polishing operations only on that specific zone, which is also objectively identified by the *X* and *Y* position values. Conversely, in the case of color map on the right side of Fig. 4, all the surface needs a complete polishing session that could be executed again by the robot: two red dotted outlines identify extended not-compliant zones, surrounded by areas of high roughness.

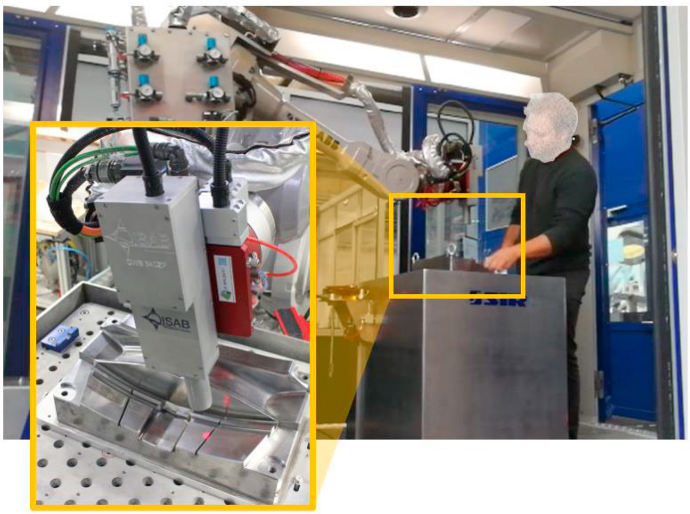

Fig. 5. Human and robot coexistence test within the reconfigurable platform while the robot is performing a measuring operation.

A further validation stage proved the HRC approach during the QA operations for the demo mould. Thanks to this configuration, when the polisher opens the cell doors to enter the robot workspace, the robot speed decreases until it stops if the safety distance threshold is exceeded. Fig. 5 depicts a live action where the human and the robot coexist in the same working space to perform operations on the demo mould, inside the orange frame. The interaction has been further improved thanks to integration of augmented reality device that directly proposes the surface quality color maps on the surfaces of the mould [25].

5. Conclusive remarks

Surface polishing is a difficult process to automate because of high sensitivity with respect to contact forces and constant quality feedback required to subsequently remove small amounts of material to reach expected quality specification without changing surface shape. Consequently, polishing is a manual process that traditionally relies on high skilled operators. Nonetheless, the introduction of robot-based polishing technologies as well as quantitative approaches to evaluate the surface quality lay the foundations for a new approach based on the supporting the human by the robots thanks to HRC technologies. The work presented provides a novel approach for HRC polishing that systematically integrate dedicated robot-polishing approaches following a specific framework that defines the roles of the human and the robot. The approach led to a demonstrative HRC reconfigurable robot polishing workcell which has been tested with respect to both polishing and collaborative capabilities. The results achieved demonstrate the effectiveness of the method proposed both in terms of manufacturing efficiency and reconfiguration capabilities. Polishing and assessment capabilities have been proved by collected surface parameters; the same parameters provide an objective way to drive the system reconfigurability. These preliminary results pose the basics for future further development of the workcell and investigation on the specific processes, such as the study of new safety countermeasures and optimization of polishing operations.

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