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Digital Twin and web services for robotic deburring in intelligent manufacturing

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Abstract

The development of modern manufacturing requires key solutions to enhance the intelligence of manufacturing such as digitalization, real-time monitoring, or simulation techniques. For smart robotic manufacturing, the modern approach regarding robot programming and process planning aims for both high efficiency and energy-awareness. During the design and manufacturing stages, optimization becomes crucial and can be fulfilled by means of appropriate digital manufacturing tools. This paper presents the development of a Digital Twin for a robotic deburring workcell along with the process planning and robot programming. Considering a large size workpiece, a new robot programming solution was implemented, based on image processing to safely re-machine only areas where burrs could not be completely removed in the main deburring routine. The work also covers the development of a new web platform to remotely monitor the robotic workcell, to trigger alerts for unexpected events and to allow the control to authorized personnel enabled by the employment of robot web services following an architectural RESTful style which establishes a communication link to the robot virtual controller. The aim of this research is to integrate the Digital Twin with the innovative proposals of Industry 4.0, offering a project-based model of smart robotic manufacturing and experience concepts such as Cyber-Physical System, digitalization, data acquisition, continuous monitoring, and intelligent solutions in a novel approach. Furthermore, the work covers energy consumption strategies for energy-aware robotic manufacturing. Finally, the results of an energy-efficient motion planning along with signal-based scheduling optimization of the robotic deburring cell are discussed.

Keywords Digital twin · Industrial robot · Web services · Robotic deburring

INTRODUCTION

In the Industry 4.0 era, factories are moving towards the smart manufacturing paradigm by implementing key solutions for system modelling, simulation, information acquisition, data analysis, intelligent decision making and more, in order to enhance production capabilities for better quality, higher efficiency and lower energy consumption. Industrial Internet of Things (IIoT) has been increasingly studied in recent years bringing technical challenges that are today closer to be overcome.

Alongside the evolution to Industry 4.0, various studies claimed that an important part in successfully implementing the Industry 4.0 strategy is to adapt higher education to the requirements of this vision, especially in engineering. (Mourtzis et al., 2018). Several studies were published in the last decade, focused on the new qualification requirements of engineers while others presented road maps to adapt manufacturing education to the requirements of Industry 4.0 by specifying mandatory changes of the curriculum or by introducing new learning conceptual frameworks and methods. Early in 2013, an educational Program was presented by (Baladrón et al., 2013), where engineers completed their traditional knowledge with more practical, industry-oriented contents, proved that this approach fosters better knowledge, skills and qualifications.

The paper presents the main elements of the authors' training setup (i.e., a new Digital Twin (DT), robot Offline programming (OLP), a new deburring algorithm, energy consumption monitoring, web platform) that offers research

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engineers the necessary robotic programming knowledge to practice and develop intelligent solutions for robotic machining and path planning along with energy consumption analysis. The training environment offers the means to tackle the innovative challenges of Industry 4.0 and get ready for the smart manufacturing demands by getting a hands-on experience on concepts such as cyber-physical systems (CPS), virtualization, process planning, and interoperability concerning workcell components. Furthermore, the new web platform enables research engineers to get accustomed with specific robotic cloud technologies, manufacturing process monitoring and intelligent decision-making.

The employed software tools are currently used by engineers in industry, making the knowledge acquired a valuable skill for devoted researchers. For the development of the DT, ABB RobotStudio provided the necessary environment to virtualize the robotic workcell, to generate a collision-free tool path and to program the robot via OLP techniques by taking into consideration sensor data and virtual models of physical components included in the physical workcell, thus simulating the process, analyzing the motion results, and evaluating the robot energy consumption.

Additionally, ABB RobotStudio was employed to define a virtual controller which runs the robot considering the workcell sensors layout that was mapped to be remotely accessible via the web platform. The platform uses web services to communicate with the virtual robot controller and offers the most suitable solutions for data acquisition, data storage, process monitoring, safety, and control. Data can be collected continuously from the physical workcell, and relevant information can be stored in a database. With well-defined manufacturing Key Performance Indicators (KPIs), the production volume can be monitored, and the cell reliability and efficiency can be evaluated. Data visualization tools have been implemented to the web platform for real-time monitoring and condition-based alerts have been set up to trigger warnings for unexpected events via a messaging system. For the development of a messaging bot, ActiveChat's Visual Builder was employed to set up the alerts along with appropriate instructions for authorized personnel offering the means to react accordingly in a timely fashion.

The main contribution of the holistic approach is bringing together Industry 4.0 specific concepts (i.e., virtualization, OLP, image acquisition and processing, energy-aware robot programming, and process monitoring) to work seamlessly, collecting data, and presenting it in interactive visualization modules enabled by robotic web services.

Robotic path planning strategies for machining have been well covered in the literature, although focusing mainly on machining processes such as deflashing of metal casts or finishing of stir-welded corner joints and on the employment of tools with active or hybrid control systems, specific for quality precision machining work. This research fills a gap by studying the use of a tool with passive radial compliance in a robotic process of deburring an injection molded plastic workpiece.

The aims of this work are to offer a detailed study on the development of a DT model of a physical robotic FMC and of a web-based platform along with an in-depth robotic OLP technique, and to propose a deburring solution based on an algorithm that generates the machining toolpath of partially removed burrs after video inspection. The paper continues with a general study of the energy consumption of the industrial robot, describes the benefits after implementing the deburring solution and presents the monitoring capabilities of the web platform on the robotic FMC.

In the second section of the paper, relevant concepts for modern robotic manufacturing, robotic deburring and toolpath planning, robot energy consumption, remote monitoring and related work are discussed. In the third section, the new DT model and the new toolpath algorithm are presented, along with discussions on robot programming and energy consumption. Another contribution of the work is presented in the fourth section and consists in a novel web platform which is used for remote monitoring and control of the robotic deburring cell. The results are summarized, and future planned activities are discussed in the last section.

Related work

Modern robotic manufacturing systems

Cyber-Physical Systems (CPS), Digital Twins (DT), Cloud Computing (CC), Internet of Things (IoT), Big Data Analysis (BDA), sensor technologies and machine learning (ML) techniques are all enabling concepts for intelligent manufacturing and taking into consideration recent developments, new trends in research and design have emerged for smart factories.

The DT of a manufacturing system is described as a sensor-enabled digital model of a physical asset that simulates the object in a live setting (Grieves, 2015) and over the past decade more definitions have arisen from industrial-filed perspectives (Stark et al., 2017), (Zhuang et al., 2018), together with their use in various industries, such as manufacturing (Tao & Zhang, 2017), (Zhang et al., 2017), (J. Wang et al., 2019), (Tong et al., 2019) aerospace (Tuegel et al., 2011), (Uzun et al., 2019), automotive (Vachalek et al., 2017), (Tharma et al., 2018) and even healthcare (Liu et al., 2019), (Rivera et al., 2019). In the most recent studies, (Lim et al., 2019), (Barricelli et al., 2019), the authors emphasize both the major role of DTs in a wide range of applications, including manufacturing control, system maintenance, robotics, and associated financial advantages.

Cyber–physical interaction and integration is an important prerequisite for smart manufacturing. CPS are known to be multidimensional and complex systems that integrate the cyber world and the dynamic physical world. While DTs are digital copies of physical entities that can simulate and reflect their behavior through modeling and simulation analysis, make predictions and control their future states through feedback, CPS consider sensors and actuators as the main modules. Both CPS and DTs pave the way for smart manufacturing by forming a closed loop between the cyber/digital and physical worlds based on state sensing, real-time analysis, information feedback, scientific decision-making, and precise execution (Tao et al., 2019).

Several papers also focused on the robustness and intelligence of CPS and DTs, and stated unique requirements (Tomiyama & Moyen, 2018) for their security (Humayed et al., 2017), (Wu et al., 2017), resilience as a response to the processes need for scalability, efficiency and reliability to generate trustworthy data (Xu & Duan, 2019).

For CNC machining processes, the Twin Control follows the CPS concept and aims to improve the performance and productivity of machine tools at each life-cycle stage. An increasing interest for machine tools virtualization is visible in the raising number of published works for DTs for CNC machining operations (Armendia et al., 2019) and tool life prediction (Luo et al., 2020).

The virtualization concepts were also recently discussed for robotic manufacturing, although mostly focused on robotic assembly applications, involving collaborative robots (Bilberg & Malik, 2019) or reconfigurable robotic workcells for small-batch production (Priggemeyer et al., 2018). Erdős et al. also presented an approach to transform already existing workcells to parametric digital twins and tackled the challenges of robotic finishing, such as grinding and polishing of cast aluminum parts. They demonstrated that the DT is able to realize accurate tool path generation for the physical workcell (Erdős et al., 2020). A methodology for advanced physic-based modeling aiming to enable the DT of an industrial robot arm in predictive maintenance applications was proposed in (Aivaliotis et al., 2019).

The purpose of this paper is to fill a gap in the literature for virtualization techniques in robotic machining by presenting the DT of a robotic workcell for deburring plastic parts of large size.

Robotic deburring

Robotic systems are known to be cost-effective solutions that have the potential to fully automate the deburring processes as a result of their high flexibility when moving along the edges of complex shaped parts. The drawback of this solution is that the stiffness of the mechanical structure of the robot is low and problems arise to tune the accuracy of the tool path with tolerance specifications of the workpiece (Ivan et al., 2015). Intelligent solutions to overcome these problems arose, such as the robot tool compliance, workpiece point cloud matching, force feedback or vision guided trajectory planning. Liao et al. developed a double compliant tool head that controls the deburring force according to the variation of the geometry in order to maintain a constant contact stress between the tool and the part (Liao et al., 2008). Wang et al. proposed an intelligent compliance control solution using fuzzy logic (X. Wang et al., 2006) and recently Berselli et al. proposed a virtual prototype of a radial-compliant spindle to optimize the deburring efficiency (Berselli et al., 2019).

Toolpath planning solutions for robotic machining have emerged to address the need for faster robot programming. Kuss et al. presented an iterative algorithm that compares and matches the point clouds derived from the workpiece CAD model with a sensor point cloud obtained from a 3D measurement of the part (Kuss et al., 2016) and Abele et al. presented a tool path speed optimization solution for deburring cross holes of complex parts (Abele et al., 2016). A hand-eye, vision-assisted robotic solution for finishing stir-welded parts was presented in (Gurdal et al., 2019), in which the robot is equipped with a line structured laser sensor and a pneumatic spindle with an adjustable deflection unit. The authors presented a scan-and-machine approach consisting of scanning and locating the workpiece in the robot coordinate system, automatic path programming and process parameter planning. Villagrossi et al. proposed a human mimicking control strategy to remove burrs of hard material workpieces on the basis of force feedback by removing thin layers of material each time (Villagrossi et al., 2018). Caesarendra et al. discussed the implementation of machine learning and cloud computing to improve deburring processes in aerospace manufacturing (Caesarendra et al., 2019).

Process simulation for tool path planning and generation can increase milling productivity and part accuracy. Leftover burrs may occur during milling due to the peculiarity of the tool with radial compliance. Compliance is the ability of a tool to maintain contact and cutting force with the workpiece. It can be achieved through a variety of techniques that include both active and passive force control systems.

Active control systems require a data link to the robot controller to provide information and therefore are closed loop systems. Active force control tools deliver real-time prompts to the robot to change its program trajectory as defined by a controlled correction routine. This can adjust the path speed and the cutting forces, but active systems are typically more expensive than passive devices, however they offer more accuracy and repeatability. Passive force control systems do not measure any cutting forces, but simply adapt to the part shape and apply a constant force. They are best suited for applications that have relatively consistent burrs or flash but have poor part-to-part tolerances. These systems greatly reduce gouging of the part by the cutter.

Radial compliance allows the movement from a center position through 360 degrees along a radius of compliance with a constant contact force in milling machining. Because the cutting action is radial, they are also well suited for removing parting lines and flash from cast parts. For a more in-depth read about radial compliance tools, the authors recommend Berselli et al.'s paper on a virtual prototype of a pneumatic compliant spindle (Berselli et al., 2016) and Ivan et al.'s study of robotic low force milling operations using radial compliant end effectors (A. M. Ivan et al., 2019).

A vision-guided robotic system (Leo Princely & Selvaraj, 2014) was conceived for the deburring of simple 2D workpieces to avoid OPL procedures and recently, Rahul et al. proposed another approach to identify burrs for 2D workpieces using image processing and to generate trajectories (Rahul et al., 2019). However, both approaches generate the toolpath required to deburr the complete profile of the workpiece and do not presume that due to the tool's radial compliance and burr thickness, some burrs could be only partially removed. Using laser measurement systems to scan the workpiece, to detect its position in the robot workspace, to generate approximate points and a sequence of frames that describe the desired poses of the tool frame are also covered in the literature for robotic machining processes such as deflashing of metal casts, finishing of stir-welded corner joints or edge deburring of aero engine components (Jayaweera & Webb, 2010). Such solutions use active or hybrid control systems, or other offline/online error compensation strategies (Schneider et al., 2016). These approaches for toolpath planning (which are also more costly) are not well suited for light deburring/deflashing where part tolerances are poor and radial compliance tools are used, as it is our case.

The present work aims to address the robotic deburring literature by focusing on tools with passive force control, specifically tools with passive radial compliance and by proposing a deburring algorithm that reduces the robot energy consumption by optimizing the number of passes in the deburring routine only in areas with partially removed burrs caused by the tool's passive radial compliance limitation.

Robot energy consumption

Reducing the energy consumption (EC) of the robot is an important step to improve the manufacturing system's efficiency. Several studies have been conducted focusing on the hardware aspect by considering strategies such as a lighter design of components or by using energy storing and recovery devices. Another approach focuses on the software aspect to enhance the motion planning via trajectory planning or operation scheduling. In the optimization stage, the robot's EC is influenced by the operating parameters and constrained by the workcell layout, productivity requirements and environmental operating conditions.

In 2014, Paryanto et al. published a study on the EC of a robot arm in an assembly system. Later on, they proposed a modular model of a robot to analyze its power consumption and dynamic behavior and demonstrated that the power consumption can be predicted (Paryanto et al., 2014), (Paryanto et al., 2015). Studies on minimizing the EC by optimizing the robot trajectories proved to be efficient as well (Hansen et al., 2012), (Pellicciari et al., 2013). In their work, Bukata et al. presented an approach to optimize the EC of robotic cells as a whole. More recently they proposed a new algorithm designed to minimize the EC by changing the robot speed, taking into consideration the robot positions as well as the power-saving modes (Bukata et al., 2017), (Bukata et al., 2019). Uhlmann et al. conducted a study on EC of industrial robots for machining processes and their experimental tests also showed that the robot movement speed has a major impact on the EC along with the cooling systems (Uhlmann et al., 2016).

Nevertheless, the literature shows a lack of studies focused on energy consumption monitored in robotic deburring processes. The presented paper aims to contribute to the research literature for energy efficient usage of industrial robots employed in deburring processes as a result of path planning optimization.

Remote monitoring and control

Equipment performance and condition monitoring has always been an essential part of the information systems used in industry to improve effectiveness and to minimize unplanned downtime. The widespread deployment of various sensors has made smart manufacturing possible. Nowadays data from various manufacturing objects, such as energy consumption, temperature or vibration can be assessed in real time. Smart monitoring provides graphical visualization of the collected data and alerts when abnormality occurs.

Monitoring of the manufacturing systems can be classified into two main groups: monitoring the status of resources (related to machinery and environment monitoring, such as machine workload, downtime, performance, etc.) or monitoring the status of jobs (related to data of each task, sequence, estimated production time, etc.).

Monitoring the manufacturing system does not directly control the physical system but it tracks it. Detailed status on every physical system is supported by key performance indicators (KPIs) such as schedule attainment, availability, quality rate and overall equipment effectiveness. Studies on Continuous and Discrete control operations have emphasized the importance of monitoring tools and techniques (Ramis Ferrer et al., 2018).

In a traditional robot cell, the service modules are integrated with the control system and physical components locally. A web-based robot cell aims to control the physical devices remotely over the network. Recent studies for cloud manufacturing environments, cloud robotics and control systems as services have addressed the advantages and challenges of having a remote control-access to a manufacturing system. The aspect of security has also been a research topic for Industry 4.0 conceptual frameworks and other works have shown how cyber-physical attacks (Gollmann et al., 2015) can be identified and counter-measured for CPS (Munteanu et al., 2018) and specifically for Industrial Robots (Quarta et al., 2017).

In summary, the work presented in this paper explores intelligent solutions for modern robotic machining and provides additional insights for readers to transform the robotic manufacturing DT towards a CPS architecture interlinked with IoT where the manufacturing system's capabilities can be extended and reconfigured. The paper tackles the challenge of using a tool with passive radial compliance in a robotic deburring process by employing a new algorithm to compensate for the tool's deflecting limitation by generating the deburring toolpath in areas where chips have been only partially removed. The presented DT offers a good understanding on the impact the robot work cycles have on the energy consumption and provides the means for energy-efficient robotic deburring though offline simulation and OLP. The web platform uses robot web services to communicate with the robot controller (virtual or real) to collect and present data focused on the robot energy consumption and cell productivity (parts finished over time).

The Digital Twin of a robotic deburring workcell

Modern CAD tools were employed for the modelling of the workcell components in accordance with their physical layout. Efficiency and reliability were the main requirements for the DT representation. The proposed virtual model, which is illustrated in Fig. 1, offers complete control on the manufacturing process with regards to the design, planning, testing, collision avoidance, fault detection, monitoring and process optimization.

The manufacturing cell comprises a 6 DoF articulated arm robot, ABB IRB 4600-40/2.55, equipped with a pneumatic end-effector with radial compliance, ATI Flexdeburr RC300, that deburrs an injection molded plastic workpiece. The use of an automatic system, ATI QC-41, allows the change of the deburring tool with a vacuum end-effector for manipulating the workpiece.

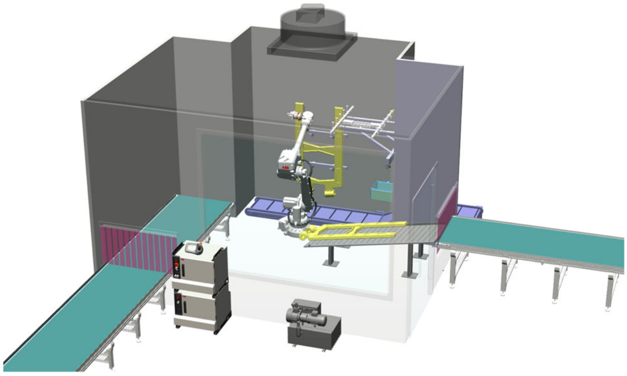


Fig. 1 The Digital Twin of a robotic deburring workcell

Virtual robot controller and offline programming

The robot toolpath was created to deburr the workpiece by defining reachable targets choosing the most appropriate robot configurations for the inverse kinematics solver to reach all the target points. The robot movements were programmed to change the tools, and to pick up or place the workpieces from the gravitational aligning table to the fixture system and from the fixture system to the outfeed conveyor. Appropriate speeds together with the movement type, whether linear, circular, or joint movements, have been defined for all the moving instructions. Since workcell components are present in the robot's reachable space, the robot program was also checked against collisions.

Four different *tool center points* (TCP) were set for: • the robot's tool mounting point, • the automatic changing system QC-41's master plate, • the deburring tool and • the vacuum gripper. These TCPs are illustrated in Fig. 2. When the robot reaches a programmed target, it aligns the TCP's orientation with the target's orientation.

In addition to robot motion instructions, events have been defined based on I/O signals which were created as communication channels between the controller and the external equipment, for instance to start the outfeed conveyor once a workpiece was positioned by the robot as programmed, or to switch on or off the vacuum when the vacuum gripper is used.

After validating all robot motions, the robot program was uploaded in the virtual controller, which now stores each target position and orientation, robot configurations and sequences of moving instructions. The robot deburring toolpath and the sequences of robot movements are illustrated in Fig. 3 (1), respectively Fig. 3 (2 and 3).

The reliability of the entire system and the robot interaction with the system is ensured by the programming based on signals provided by the sensors. The workcell sensors layout has been mapped to both the virtual controller and further on in the web platform confirming that sensors information is

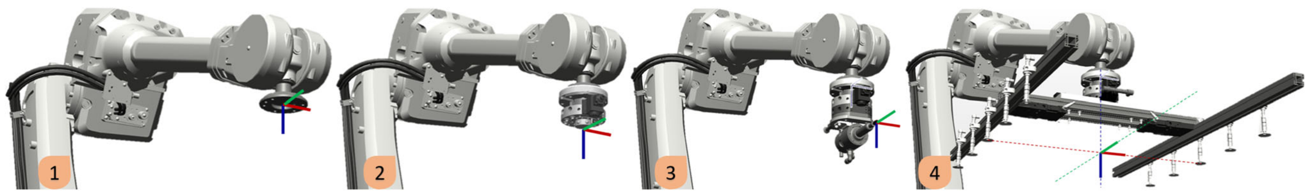
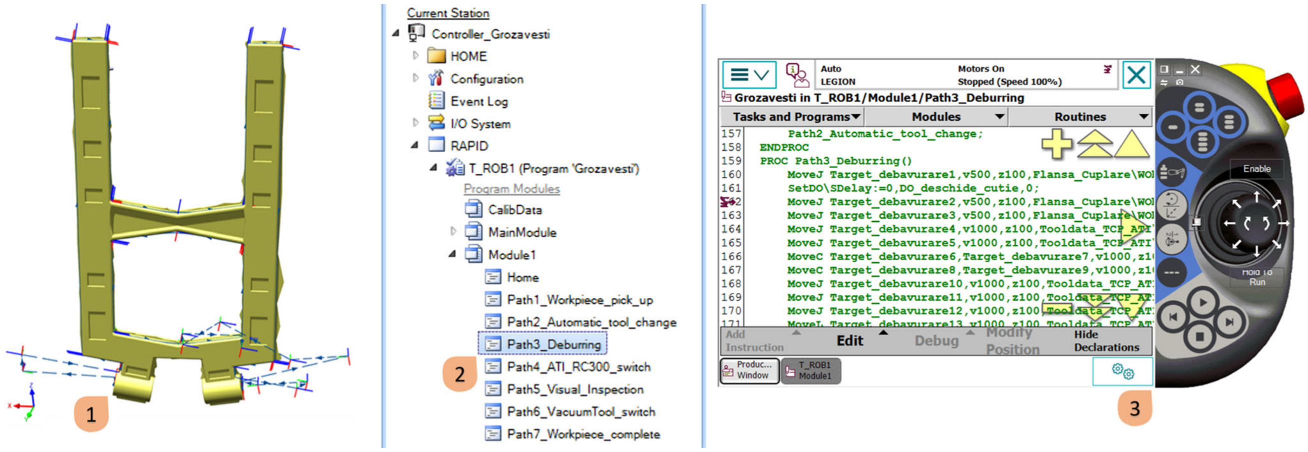


Fig. 2 Tool Center Points: 1 - robot tool mounting point. 2 - QC-41 master plate mounting point. 3 - deburring ATI RC300 tool. 4 - vacuum gripper point



```
        Path2_Automatic_tool_change;
    ENDPROC
    PROC Path3_Deburring()
        MoveJ Target_debavurare1,v500,z100,Flansa_Cuplare\WOl
        SetDO\SDelay:=0,DO_deschide_cutie,0;
        MoveJ Target_debavurare2,v500,z100,Flansa_Cuplare\WOl
        MoveJ Target_debavurare3,v500,z100,Flansa_Cuplare\WOl
        MoveJ Target_debavurare4,v1000,z100,Tooldata_TCP_ATI
        MoveJ Target_debavurare5,v1000,z100,Tooldata_TCP_ATI
        MoveC Target_debavurare6,Target_debavurare7,v1000,z1
        MoveC Target_debavurare8,Target_debavurare9,v1000,z1
        MoveJ Target_debavurare10,v1000,z100,Tooldata_TCP_AT
        MoveJ Target_debavurare11,v1000,z100,Tooldata_TCP_AT
        MoveJ Target_debavurare12,v1000,z100,Tooldata_TCP_AT
        MoveL Target_debavurare13,v1000,z100,Tooldata_TCP_AT
```

Fig. 3 Robot deburring tool path (1), operations sequence (2) and the robot program loaded and shown on the robot flex pendant (3)

in sync. In addition, the reliability of the robot can also be verified by tracking the energy consumption. In cases when the DT is scheduled based on events, not all actions can be confirmed and therefore the reliability may not be assured. The efficiency is determined based on the operating times and the energy consumption. Any energy or operating time increases are visible in the web platform monitoring panel. Efficiency is not statistically calculated for a standard cycle but depends on the actual execution time of each part.

The robotic manufacturing cell OLP and simulation are further detailed in the next chapter.

Robotic manufacturing cell offline programming

The robotic deburring cell structure is illustrated in Fig. 4, together with the sensors layout. The working cycle has three main stages. *In the 1st Stage*, the plastic workpiece (wp) is brought by the in-feeder conveyor (C-in) and stopped near the S1 sensor, waiting for a signal from the S2 sensor to confirm that the workpiece can safely advance on the gravitational aligning table (AT) which assures that each workpiece (Awp) will have the same position and orientation before it is picked-up by the robot effector. A Cognex Integrated Vision System (IVS) double-checks the workpiece position previously to the pick-up by the ABB robot, which is equipped with the Schmalz vacuum gripper (Ve). After the Awp workpiece is picked up from the aligning table and therefore, not detected anymore by the S2 sensor, the C-in conveyor starts, and the waiting workpiece wp enters the cell and slides in the right position on the aligning table.

When picking up the workpiece from the sliding table, the S7 proximity sensor positioned on the vacuum gripper confirms that the workpiece to be grasped is already located in the right position before starting the vacuum. To ensure that the workpiece has been successfully gripped, the robot enters a condition loop where it is programmed to execute a short retraction movement: if the workpiece is still detected by the S7 proximity sensor, the robot will continue its movement and exits the conditioning loop, but if the workpiece is no longer detected, the robot will come back again to the workpiece and retry the picking up operation until it exits the conditioning loop. Because the workpiece is laying in a cell where plastic debris is present this conditioning loop ensures that the working cycle is not interrupted by an unsuccessful gripping of the workpiece during the pick-up process.

In the 2nd Stage, the workpiece is brought by the robot to the vacuum fixturing system (VFS), where another proximity sensor (S4) confirms that the part is in range before activating the fixturing system's vacuum and deactivating the robot gripper's vacuum. The S3 proximity sensor confirms that the robot has correctly placed the vacuum gripper in its fixture frame (VeS) and another sensor (S6) confirms that the deburring tool (Dt) is properly placed in the tool storage device.

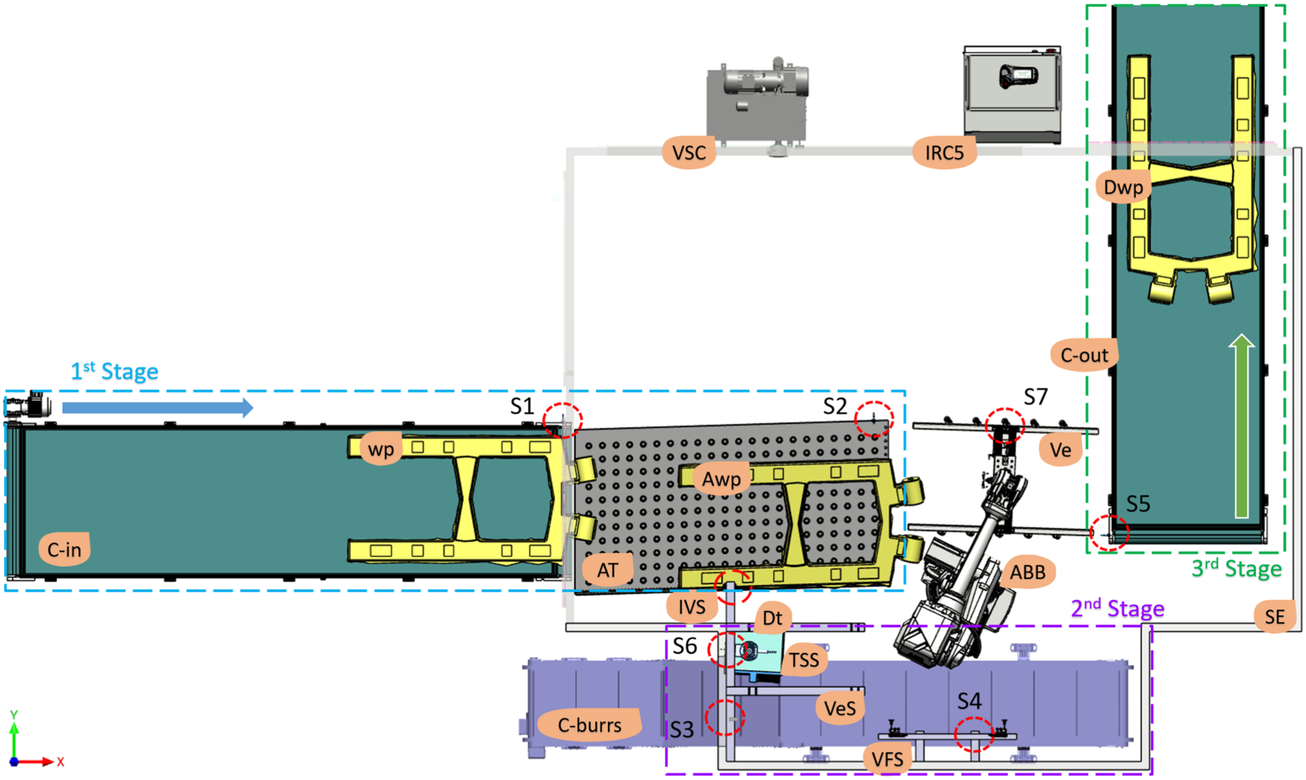


Fig. 4 Robotic deburring cell structure and sensors layout

The robot deburrs the plastic workpiece while a conveyor (C-burrs) collects all the chips from the deburring process and evacuates them from the cell. When the deburring process is completed, the robot places the deburring tool back in the tool storage system (TSS). The part is then video inspected by the robot with a camera located inside the master flange of the ATC system that follows the tool path. If burrs are still detected, a programming routine is activated to remove the remaining material from appropriate areas otherwise the robot picks up the vacuum gripper.

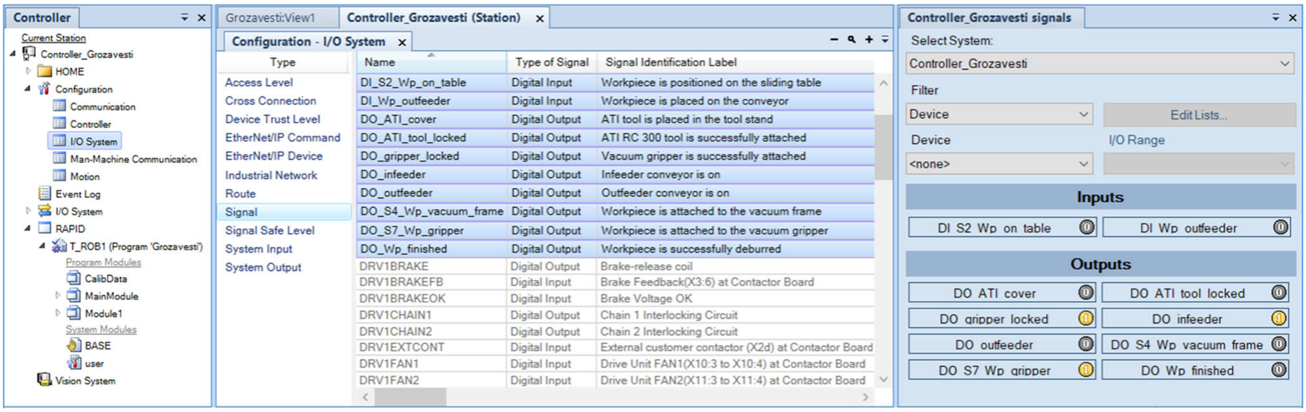
An algorithm was developed that generates the new tool-path required to remove remaining burrs captured by the visual inspection, limited only in the appropriate area where remaining burrs are present. This approach ensures that only the strictly required time is spent to remove the remaining burrs without having to redo the entire deburring process. The quality check is repeated until all the quality conditions are completely satisfied. In the next section this approach is further discussed and more details concerning the algorithm are provided.

In the 3rd Stage, the robot equipped with the vacuum gripper approaches the deburred part secured in the vacuum supporting frame. Then the robot proceeds to pick-up the part and comes closer to the out-feeder conveyor. A proximity sensor (S5) placed on the conveyor confirms that it is clear and safe for the robot to place the part on the conveyor. When the part (Dwp) is placed on the conveyor, it is detected by the S5 sensor which will stop the vacuum generator to detach the part and then will start the conveyor with a certain delay, to allow a safely retract for the robot. The work cycle restarts, and the robot will execute the operation of picking up the part from the sliding table when the S2 proximity sensor confirms that a workpiece is in the proper position.

The conceptual CAD design comprises additional extensions, such as a gravitational aligning table or a storage device for the deburring tool. Moreover, workcell components have been designed in an effort to ensure that the DT closely emulates the physical workcell such as the Schmalz vacuum supply center (VSC) and the cell safety enclosure (SE). The workflow was analyzed together with the OLP and testing, providing working cycle's optimization. All sensor signals were configured and synchronized to the virtual robot controller I/O System and are illustrated in Fig. 5.

Robotic deburring algorithm for partially removed burrs

The tool employed in this work is a passively radial compliant tool, which is particularly adept at flash removal. It is also suitable for edge deburring and removal of parting lines. The workpiece is a large sized 900 mm x 1800 mm injection molded plastic part.



Name	Type of Signal	Signal Identification Label
DI_S2_Wp_on_table	Digital Input	Workpiece is positioned on the sliding table
DI_Wp_outfeeder	Digital Input	Workpiece is placed on the conveyor
DO_ATI_cover	Digital Output	ATI tool is placed in the tool stand
DO_ATI_tool_locked	Digital Output	ATI RC 300 tool is successfully attached
DO_gripper_locked	Digital Output	Vacuum gripper is successfully attached
DO_infeeder	Digital Output	Infeeder conveyor is on
DO_outfeeder	Digital Output	Outfeeder conveyor is on
DO_S4_Wp_vacuum_frame	Digital Output	Workpiece is attached to the vacuum frame
DO_S7_Wp_gripper	Digital Output	Workpiece is attached to the vacuum gripper
DO_Wp_finished	Digital Output	Workpiece is successfully deburred
DRV1BRAKE	Digital Output	Brake-release coil
DRV1BRAKEFB	Digital Input	Brake Feedback(X3:6) at Contactor Board
DRV1BRAKEOK	Digital Input	Brake Voltage OK
DRV1CHAIN1	Digital Output	Chain 1 Interlocking Circuit
DRV1CHAIN2	Digital Output	Chain 2 Interlocking Circuit
DRV1EXTCONT	Digital Input	External customer contactor (X2d) at Contactor Board
DRV1FAN1	Digital Input	Drive Unit FAN1(X10:3 to X10:4) at Contactor Board
DRV1FAN2	Digital Input	Drive Unit FAN2(X11:3 to X11:4) at Contactor Board

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Fig. 5 Cell signals configuration in the robot controller

Taking into consideration the size of the workpiece a solution to deburr only leftover burrs rather than re-doing the complete workpiece profile, can assure an important time reduction to finish the workpiece and also benefits by an energy-wise approach. The workflow implemented is illustrated in Fig. 6 and certifies that all the burrs have been successfully removed.

The proposed algorithm uses image processing to identify partially removed burs and establish the areas to be machined. Leftover burrs may occur during deburring due to the peculiarity of the tool with radial compliance which will deflect in a direction perpendicular to the cut when thicker burrs are encountered. The proposed deburring algorithm is used to detect only the location of the partially removed burrs and machine those areas in multiple passes (iterations) based on burr height and tool cutter radius. The block "New deburring process" from Fig. 6 illustrates the routine which consists of multiple deburring passes.

Most papers found in the literature for robot paths generated based on image processing either don't cover the use of passively radial compliant tools (rather use an active compliance system) or the use case of large-sized workpieces with uneven burrs. Having the same approach of generating multiple passes based on burr height and tool cutter radius for the full workpiece, for the studied use case, it would result in a longer machining time and robot energy inefficiency since most of the burrs are removed in the main deburring routine.

To further optimize the generated robot tool path, taking into account the workpiece symmetry and burrs location, the algorithm also provides the required data for robot tool positioning and routines to safely approach the workpiece and to retract. For this study, there are four possible cases where partially removed burrs can be located: left or right side of the workpiece and on the outer or inner part. Thus, based on the XY coordinates of the detected burr, a safe routine to approach and to retract from the workpiece can be generated. The toolpath is created based on the shape and size of the video detected burr. Finally, the program is synchronized to the robot controller.

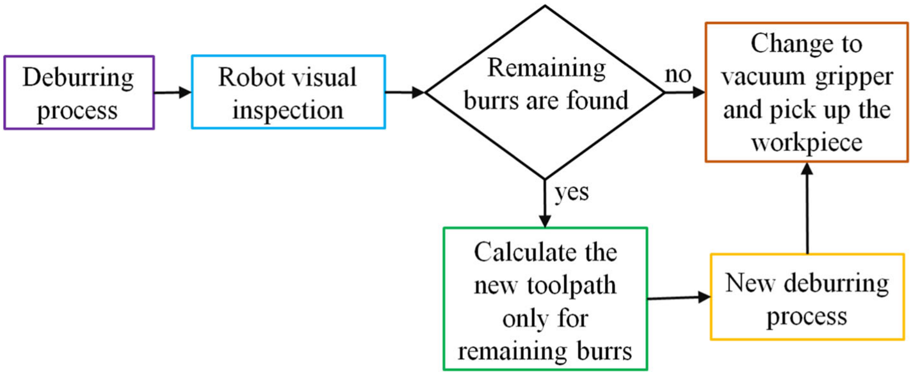
The vision system employed in the visual inspection routine consists of a high acquisition speed VGA camera. Its compact size (35 mm x 32 mm x 75.5 mm) makes it suitable for integrating it into tight spaces on the robot and mounting it inside the master flange of the ATC system. The camera model used is Cognex 8400 (embedded with image processing), having a resolution of 640 × 480, max acquisition speed of 217 fps, Gigabit Ethernet connectivity and Power supply Ethernet (PoE). A connection with the robot controller can be established via the robot controller's Integrated Vision Interface. The vision system provides targets in a coordinate system shared with the robot. The RobotStudio environment offers a toolset for part location and inspection. The authors configured and fine-tunned a vision job by defining the part the camera should locate, the inspection tool, and how the vision data is transferred to the robot program, employing the already defined Robot TCPs.

A crucial prerequisite for the vision job is to calibrate the image to real-world units [mm] by using checkerboard calibration plates with fiducial. When executing the visual inspection routine, the robot reaches the same position (robtarget) every time an image is acquired. Given its large size, the workpiece has been divided into 6 views of interest. Each view has a designated position the robot must reach and acquire an image that is next matched to its corresponding reference portion of the workpiece by employing the RobotStudio vision job.

In terms of excesive burr identification the coordinates of A, B, C, D, L, M, N, P and Q points are extracted (Fig. 8). The input values are the coordinates of the previously mentioned points and the mill radius R_m. The L point locates the part in the XOY reference coordinate system.

A reference workpiece was used in the vision job as model for the location tool to determine the position of the workpiece in XY coordinates as a fixture point. The location tool

Fig. 6 Comprehensive representation of the deburring workflow



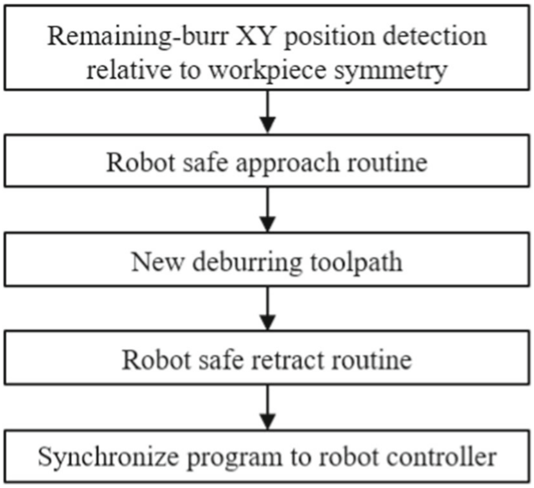


Fig. 7 Main robot programm routines to deburr leftover burrs

is part of the RobotStudio toolset for visual inspection which employs a pattern finding process consisting of two phases: training and finding. In the training phase, a region containing the reference workpiece pattern to be located was manually identified and extracted to create a trained pattern. In the finding phase, new images of inspected parts are searched for positions that exhibit maximum similarity (according to the specified metrics). Corner points (M and N) are defined on the reference part while the location tool enforces their position on the inspected part by matching the pattern feature of the inspected part and its reference.

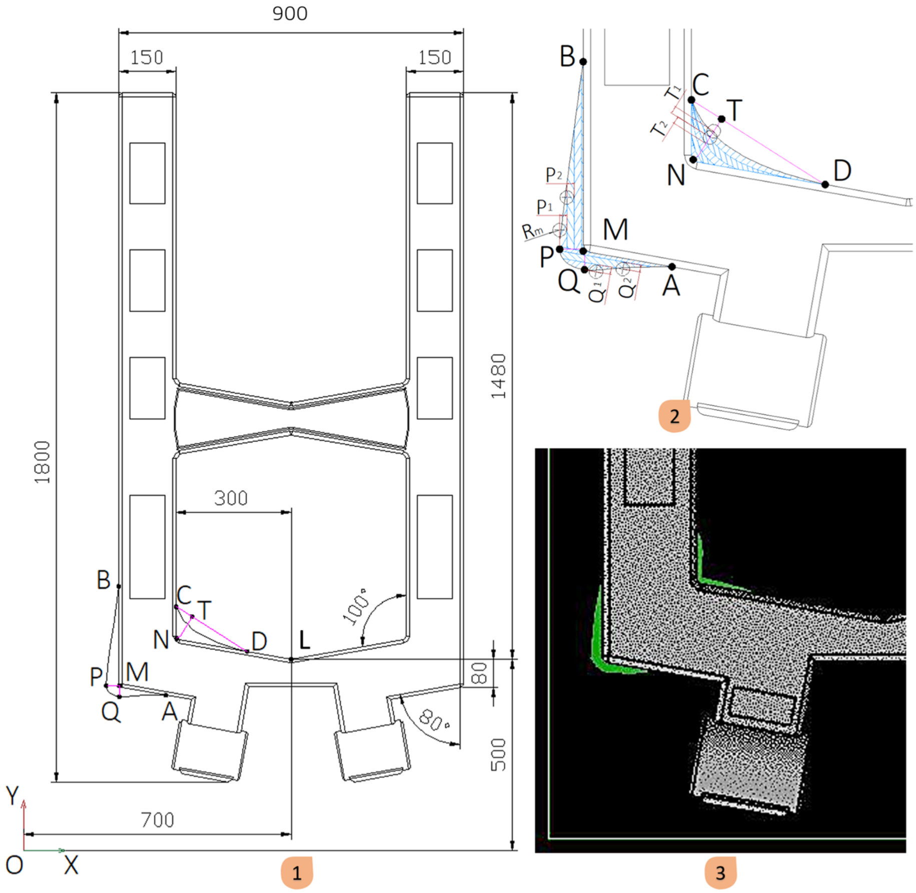
Another matching pattern process was employed to compare the inspected part to its reference to determine and to highlight the remaining defects using a bilinear pixel comparison method. Using this information, two other tools are employed: the blob presence and the edge defect detection tools. The blob presence tool performs a pixel connectivity analysis in the region of interest relative to the part fixture point. Its role is to locate the highlighted defects (light-colored connected pixels on a dark contrast, according to a specified threshold) and report their center position in XY coordinates. This information is used to determine the corresponding robot routines to approach and retract. A minimum area restriction was specified for the blob presence tool to filter out noise. The edge defect detection tool uses an array of calipers for precise locations of edge features and reports if deviations are found in the region of interest relative to the part fixture point. The max deviation (representing the burr height – point P and Q) and the min deviation (representing the burr length – point B and A) are reported in XY coordinates.

In the first stage the algorithm removes the excessive convex burrs starting from Q point. The maximum limits are defined by A, Q, P and B point coordinates. The machining strategy assumes to remove the excess material by successive milling passes parallel to the AM edge of the piece and then parallel to MB edge. Therefore, the material to be removed is divided in cutting depths equal to the tool radius. Starting from the Q and P points, that are the extreme limits of the tool path, the algorithm calculates the next trajectory using the Q and P coordinates and the tool radius Rm. The computation continues until the distance from the last point to the AM edge is less than the tool radius, when the contact point between the tool and the part is assumed to follow up the AM and MB segments, respectively (Fig. 8).

Robot energy consumption

For the deburring workcell, in an effort to optimize the robot program energy-wise, several simulations have been performed, to monitor and record the energy consumption with a tool that accurately evaluates the energy consumption. Nevertheless, as any simulation model that uses approximations, the energy data recorded is slightly understated, as we expect electromechanical losses in robot drives and operating condition influences to be oversighted by the software model. For the virtual robot, the signals of Total Motor Power and Total Motor Energy are based on an ABB robot during typical operating conditions. The purpose is to identify power usage peaks and to adjust the robot program in order to reduce the power consumption.

Fig. 8 Computational model for deburring excessive burrs. 1 - workpiece with excess burrs; 2 - burrs detail and toolpath; 3 - image processing (burrs - green)



As illustrated in Fig. 9, a record where the total energy consumption and the total absorbed power for a single work cycle has been analyzed for a workpiece where burrs were successfully removed from the first stage of the deburring process (1), as well for a workpiece where additional deburring routines were required to remove remaining burrs (2). Successfully deburred means that the robot visual inspection didn't identify any remaining burrs along the workpiece profile. Figure 9 (2) illustrates the energy recorded during a work cycle of a workpiece for which the robot visual inspection identified a single area where burrs have been partially removed, and the proposed algorithm generated a second deburring routine focused only on the identified area.

An important time in this additional machining phase is consumed by the robot to change the tool and to reach the position for this new routine. It is presumed that burrs that are not entirely removed in the main deburring routine are thicker, causing the compliant tool to deflect, and successfully removing them would require multiple passes. In the presented case study, the number of additional machining passes was calculated in respect to the tool radius. This is the reason why in this particular case the trajectory was not much shorter in the second deburring phase. As illustrated in Fig. 9 (2), the deburring of excess burr requires 3 consecutive passes. When employing a compliant tool, the maximum excessive burr that can be removed at a single pass is equal to the tool radius.

The recorded data for a simulated work cycle demonstrates how the robot speed and payload have an impact on the energy consumption. By raising the payload, the energy consumption is increasing accordingly and higher or very slow speeds lead to augmented energy consumption. Thus, the offline simulation brought a trade-off between the reduction of the energy consumption, achieving quality and productivity requirements as well. Figure 10 shows the total energy consumption report for a workpiece without remaining burrs after the first deburring operation (1), for a workpiece with remaining burrs that requires a second deburring operation in which our solution was employed (2), and one that requires a second deburring operation repeating the entire part profile (3). A validation of the simulation results is possible by comparing the data with physical records from actual measurements.

Fig. 9 Records of the total energy (marked in black) and total power (marked in orange) of the drive for the deburring process during a work cycle of a workpiece with no remaining burrs (1) and with remaining burrs (2)

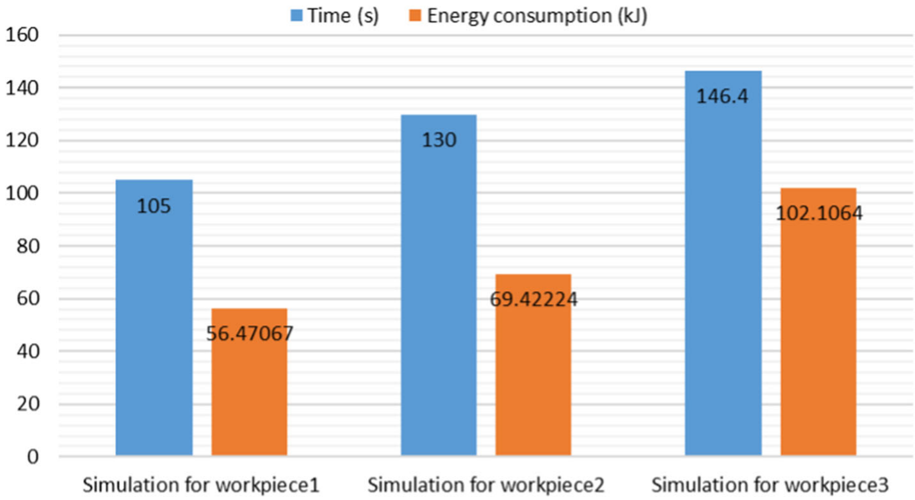


Fig. 10 Total energy consumption report for a workpiece with no excess burrs (1), with excess burrs removed in three consecutive passes generated by the proposed toolpath algorithm (2), and with excess burrs removed in 3 consecutive passes along the workpiece profile (3)

Web based platform for robotic deburring cell remote control and monitoring

A web-based approach for a manufacturing monitoring system allows the use of a wide range of devices with graphical interface support, but also has its drawbacks which are further discussed. The novel web platform was developed to access information from the virtual robot controller via web services which follow the architectural form of RESTful APIs using the HTTP protocol while the messages are composed of XHTML and JSON. A user authentication is required via login data, such as username and password, which are defined in the virtual controller. The data is stored on a local server and GUI elements are used to present the information in interactive charts and to be used for KPI reports. A messaging system is employed to trigger condition-based alerts with appropriate instructions. Based upon this data, authorized people can take informed decisions concerning the production system. All sensor signals have a digital copy in the virtual controller, as exhibited in Fig. 5. The virtual model simulates the robot behavior in the real world and provides feedback. The virtual model simulates the robot behavior in the real world and provides feedback since it can calculate robot motions and handle I/O signals. Figure 11 illustrates the required components of the web platform.

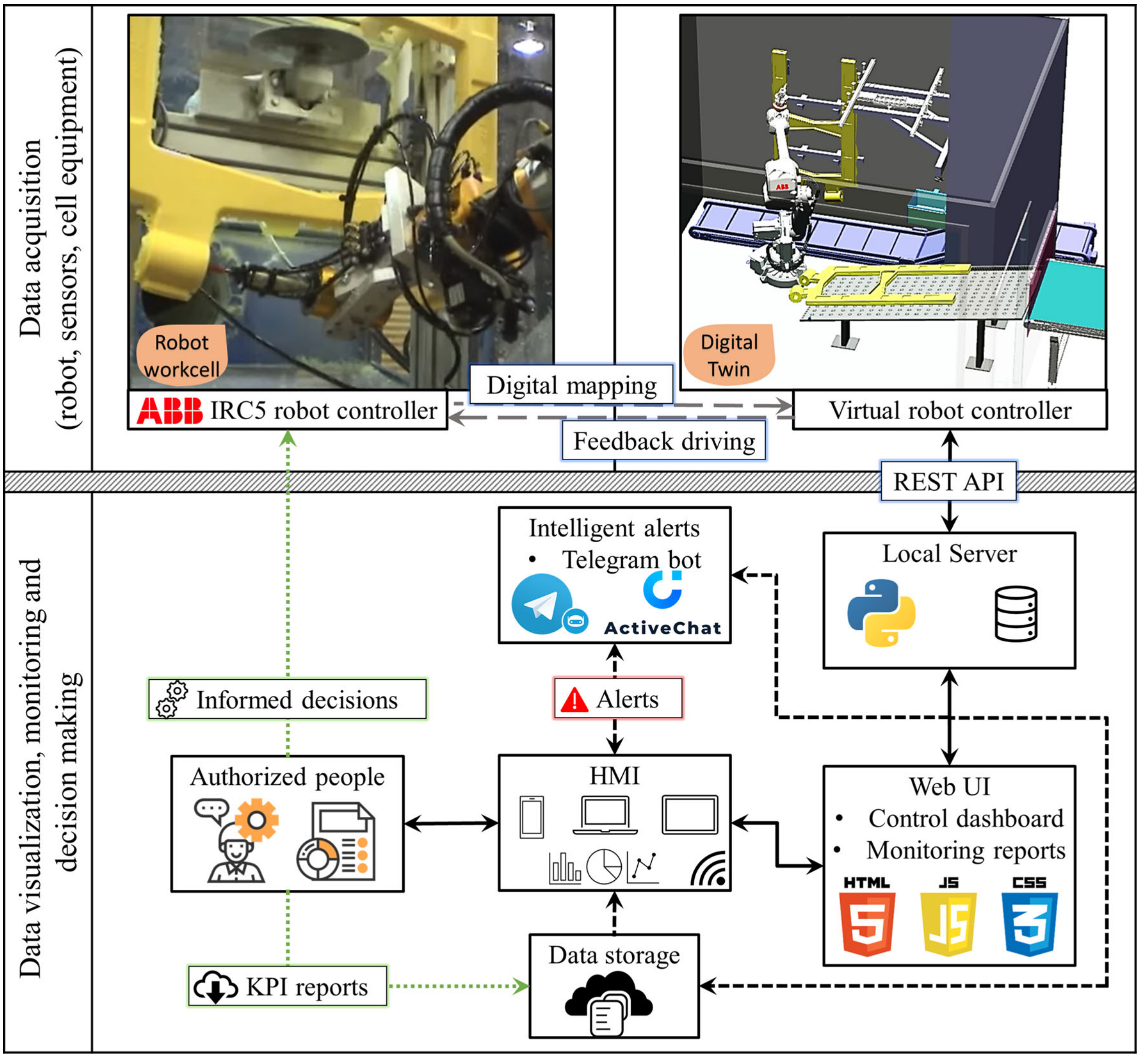


Fig. 11 Web-based robotic manufacturing platform for monitoring and control

The user interface consists of seven main parts illustrated in Fig. 13: • the 1st section allows authorized personnel to select the robot controller unit to connect with (in this case, a connection to the virtual robot controller was made); • the 2nd section displays a 3D model of the selected workcell; • in the 3rd section, the robotic deburring process can be monitored via a livestream of the DT, or alternatively by switching to a live recording of the real workcell supplied by a camera with 2 (tilt-pan) DoF; • the 4th section illustrates the remote control board, which allows authorized personnel to stop the process in case of emergency and allows control over the DT simulation (such as starting, stopping, or resetting the virtual simulation); • the 5th section illustrates the remote monitoring board, where the current state of selected manufacturing process sensors is displayed; • in the 6th section, an Energy Consumption interactive graph is displayed • the last section is an interactive manufacturing volume graph. System alerts can be set based on the recorded data in case of abnormal energy consumption, breakdowns or decreases of the daily delivery in the manufacturing batches.

Web platform alerts

For triggering and sending customized notifications and preset alerts to authorized users, a bot messaging method was chosen as it can be easily integrated with a database. A Telegram bot is a small program that can embed in Telegram chats and perform specific roles. Additionally, authorized personnel can also react fast and accomplish specific actions when a notification is received. A sample of the received message alert is illustrated in Fig. 12 reporting unexpected peak energy consumption along with two possible options for the user to act in response.

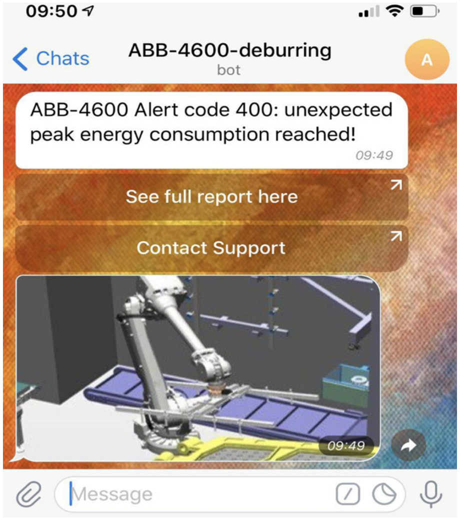


ABB-4600 Alert code 400: unexpected peak energy consumption reached!

09:49

Fig. 12 Telegram bot for alerts - phone screenshot

Remote monitoring and control

The design of a monitoring system involves interdisciplinary skills with regards to data acquisition, data storage, etc. for both the hardware and software aspects. A data storage module is responsible for data archiving, distribution, and storage. For the present web platform, the data stream was stored on a local server in JSON format and continuously synchronized to the web platform. Various factors were considered such as data-streaming speed, storage size, and exchangeability as they are some of the key factors to be considered in order to establish the efficiency of a production monitoring system. Monitoring the system close to real-time demands good quality data-streaming speed (bottlenecks could occur on both software and hardware sides). These factors determined the time intervals at which the energy data is collected, for how long it should be stored and whether compressing methods should be used, correlating with the storage space needed.

In the visualization module, where charts are presented, the collected data (i.e. energy, completed parts) is plotted in time order. The main purpose of a visualization module is to present complex data in a simple way to allow rapid and efficient decisions to be taken by the supervising personnel. By comparing the actual data with guidelines, authorized operators can draw conclusions whether the manufacturing process is stable and effective.

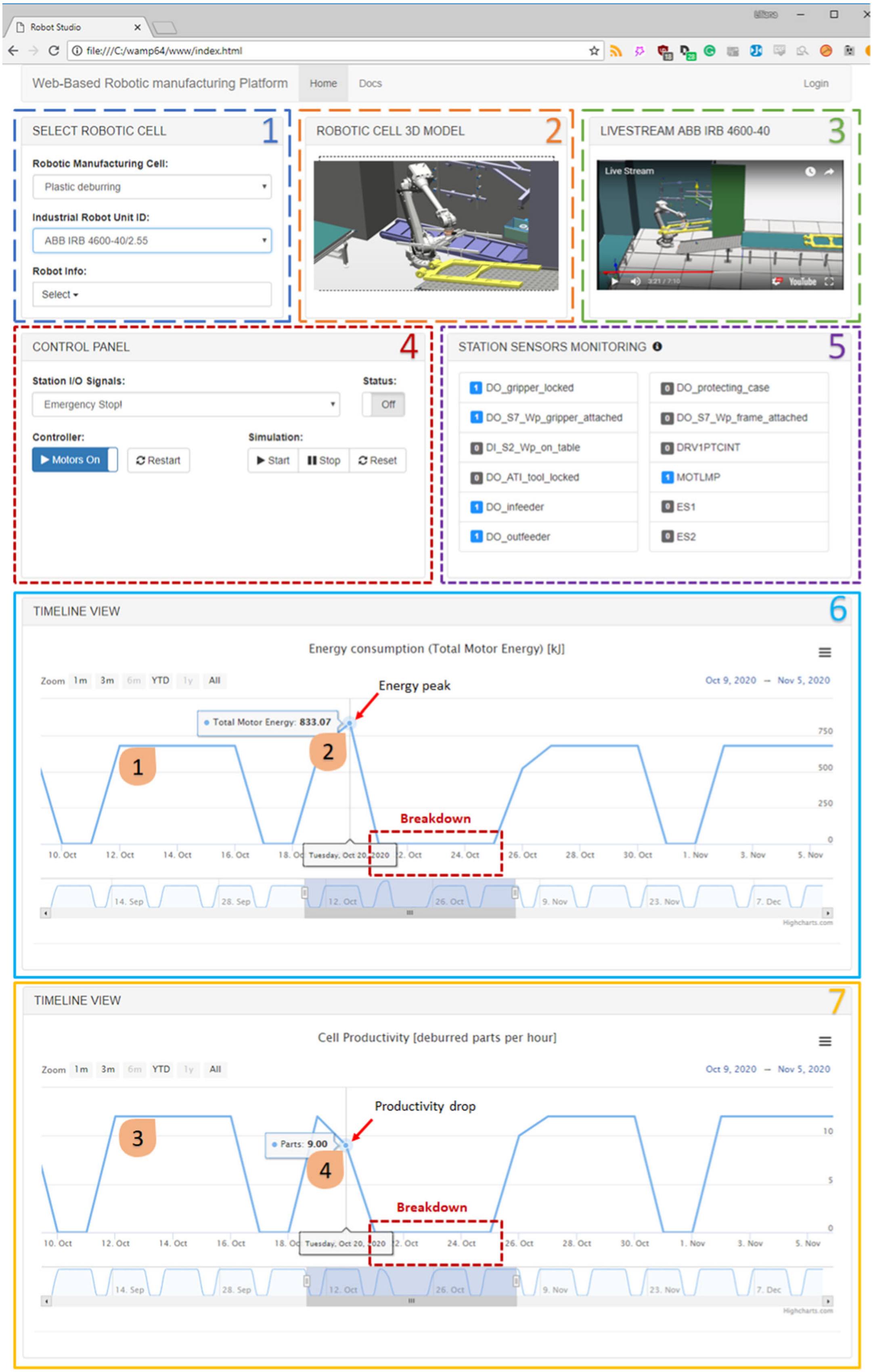
The actions implemented to the web platform presented in this paper allow authorized remote control-access over the manufacturing process with the ability to stop the process in case of an emergency, as well as the capability to stop or to restart the robot controller. The proposed web-based platform was focused on providing a remote control and monitoring system for Cyber Physical Robotic Systems (CPRS) in the Industry 4.0 context. Future work may be focused on the cyber-physical security and other KPIs driven events that can be implemented as the web-platform is designed to easily grow into a System of CPRSs.

Discussion of the results

The paper encompasses the development of a DT for a robotic deburring cell together with a web platform for remote monitoring and control. The work offers to research engineers the necessary means to tackle the innovative challenges of Industry 4.0 by setting up an environment where they can get a hands-on experience on concepts such as CPS, virtualization and interoperability concerning workcell components. Upon that, they can use the web platform and further experiment with continuous control principles and data acquisition from the robot controller or easily scale the monitoring system across multiple robotic cells. Moreover, the work offers the tools and space for engineers to practice and develop intelligent solutions for robotic machining.

The platform is currently employed in training and teaching activities in EUR-ACE labeled Robotics bachelor and master study programs running at the Faculty of Industrial Engineering & Robotics from Politehnica University of Bucharest. The training program enables the students to increase their understanding of the principles and operation of industrial robots used in modern manufacturing applications. Through project-based teaching, the students get an insight into the design and control principles of industrial robots and robotic workcells (CAD & OLP), a hands-on experience working with software applications used in the manufacturing environment, and a PLM engineering perspective. The platform is also employed for programming tasks of the electrical driving systems, for the definition of the working cycles and to determine the speeds and the travel distances of the pallet during the work cycles. A study concerning the robotic engineering education in the context of Industry 4.0 was published in (Nicolescu et al., 2019).

The paper also covers the offline programming of the robotic workcell along with an original solution for optimal deburring of excessive burrs. Although the main challenge of using industrial robots for milling processes is their lack of stiffness, modern solutions such as tools with radial or axial compliance together with smoother tool trajectories and advanced improvements in accuracy and stiffness compensation methods can ensure that workpieces are machined within intended tolerances. Generating robot trajectories via image processing solutions were proposed in recent research for robotic deburring. However, all the achievements were focused on generating the complete toolpath without taking into consideration drawbacks when using radial-compliance



Robotic Manufacturing Cell: Plastic deburring

Industrial Robot Unit ID: ABB IRB 4600-40/2.55

Robot Info: Select

Station I/O Signals: Emergency Stop!

Status: Off

1 DO_gripper_locked	0 DO_protecting_case
1 DO_S7_Wp_gripper_attached	0 DO_S7_Wp_frame_attached
0 DI_S2_Wp_on_table	0 DRV1PTCINT
0 DO_ATI_tool_locked	1 MOTLMP
1 DO_infeeder	0 ES1
1 DO_outfeeder	0 ES2

Fig. 13 Web based platform for remote monitoring and control of a robotic deburring cell. 1&3 - expected energy consumption and productivity; 2&4 energy consumption peak with a decline in productivity followed by a breakdown period

tools, such as the possibility to remove burrs only partially. From this perspective, the paper presents an improved method that is beneficial in this application for large workpieces. A new robot programming solution based on image processing was implemented to safely re-machine only areas where burrs could not be completely removed in the main deburring routine.

The DT offers a good opportunity to better understand how the robot work cycles have an impact on the energy consumption. EC is getting considerable attention as EC models and optimization approaches are very well covered in recent studies since the energy-efficient use of IR has a great impact on the production costs. Moreover, the work highlights the essential knowledge for modern robotic manufacturing on energy-aware robot programming. Since there are several methods for reducing the energy consumption of IR discussed in the literature, this work followed another perspective on energy-efficient motion planning along with signal-based scheduling optimization.

The main goal of the presented web platform was to conceive a simple and efficient way to monitor a robotic manufacturing system in real-time in an industrial setting, by presenting the data collected from the virtual controller in history-based visualization modules, focused on robot energy consumption, as well as workcell productivity, to notify authorized personnel on pre-set alerts and provide the means to react accordingly. With the use of a secure remote connection, the remote control can be easily extended to allow the remote transfer of the programs to the robot controller. Before the COVID-19 pandemic, the authors did not consider the need of an extended remote control over a robotic manufacturing process and did not acknowledge the necessity to perform remote work in the robotic manufacturing system. Certainly, expanding the remote control of a robotic process is now a possible direction for future work.

The system can be extended to collect, visualize processes, and analyze data across the factory floor, making it central for operations. Real-time production data and call-to-action alerts help improve operational efficiency and cost-effectiveness. The robot-based manufacturing system can be improved by the wireless sensor network to acquire the dynamic status and queries, and then be driven by remote control methods towards trustworthy performance using AI procedures and machine learning algorithms. The feasibility of future implementations was also reported in the literature (Wang & Wang, 2021).

A possible limitation in this study that could be addressed by future research is that the proposed deburring algorithm has been purposefully developed to complement passive compliant deburring tools. These are not assisted by a 6-DoF force & torque sensorial system, which is mandatory for tools with an active control system, as their main perk is to fully remove burrs while respecting part tolerances. The nature of the current technology used to develop the web platform brings to light another possible limitation of this study: the remote-control functionality only allows authorized personnel to stop the robotic process in case of emergency due to the typical operation mode of a robotic FMC since the remote control is restricted in the programmed task.

Conclusions

The present work illustrates key concepts of modern manufacturing such as virtualization, smart energy-aware robot programming, data acquisition, process monitoring and control in a synergic approach. The aim of this research was to develop the Digital Twin of a robot deburring cell together with a web platform to continuously monitor the manufacturing process, to allow authorized control on the physical workcell for emergency stop, to alert on unexpected event occurrences, to track the workcell productivity and part quality, and to provide relevant and trust-worthy information that can be used for KPI reports.

The following aspects have been considered in this paper:

- The deburring algorithm which uses image processing to identify partially removed burrs and decides the areas to be machined.
- Ensuring a successfully deburred workpiece employing a tool with radial compliance, while minimizing the energy consumption.
- The web platform to remotely monitor the robotic deburring process (tracking the energy consumption and the number of machined parts), allowing remote control over the robot to authorized personnel.

A CAD-CAM environment was used to design a digital copy of a physical robotic deburring cell, to set up a virtual robot controller along with all workcell digital sensor signals, to plan the manufacturing process and to program the robot. The challenges of modern robotic milling along with energy-aware strategies for industrial robotics, benefits of and threats to remote-monitoring solutions were also discussed.

The available equipment enables the authors to continue the work with new developments of intelligent strategies for digitalization, energy-aware trajectory, and process planning, along with robotic specific cloud technologies for monitoring, control, and smart decision-making. Work is in progress to extend the web platform to remote-monitor and control new robotic systems, to develop and implement other Industry 4.0-specific solutions such as machine learning techniques for robot programming, as well for predictive maintenance and security defenses. The system can be expanded to collect, visualize processes, and analyze data across the factory floor, making it central for operations.

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References

Abele, E., Haehn, F., Pischan, M., & Herr, F. (2016). Time Optimal Path Planning for Industrial Robots Using STL Data Files. *Procedia CIRP*, 55, 6–11. https://doi.org/10.1016/j.procir.2016.08.038

Aivaliotis, P., Georgoulias, K., Arkouli, Z., & Makris, S. (2019). Methodology for enabling digital twin using advanced physics-based modelling in predictive maintenance. *Procedia CIRP*. https://doi.org/10.1016/j.procir.2019.03.072

Armendia, M., Cugnon, F., Berglind, L., Ozturk, E., Gil, G., & Selmi, J. (2019). Evaluation of machine tool digital twin for machining operations in industrial environment. *Procedia CIRP*. https://doi.org/10.1016/j.procir.2019.04.040

Baladrón, C., Jiménez, M. I., Aguiar, J. M., Carro, B., & Sánchez-Esguevillas, A. J. (2013). Improving teaching in engineering education: Adjunct enterprise professors programme. *Journal of Intelligent Manufacturing*. https://doi.org/10.1007/s10845-011-0546-0

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: definitions, characteristics, applications, and design implications. *IEEE Access, 7,* 167653–167671. https://doi.org/10.1109/ACCESS.2019.2953499.

Berselli, G., Pellicciari, M., Bigi, G., & Razzoli, R. P. (2019). Design optimisation of cutting parameters for a class of radially-compliant spindles via virtual prototyping tools. *International Journal of Computer Aided Engineering and Technology*, 11(2), 232–252. https://doi.org/10.1504/IJCAET.2019.098138

Bilberg, A., & Malik, A. A. (2019). Digital twin driven human–robot collaborative assembly. *CIRP Annals*, 68(1), 499–502. https://doi.org/10.1016/j.cirp.2019.04.011

Bukata, L., Sucha, P., Hanzalek, Z., & Burget, P. (2017). Energy optimization of robotic cells. *IEEE Transactions on Industrial Informatics, 13*(1), 92–102. https://doi.org/10.1109/TII.2016.2626472.

Bukata, L., Šůcha, P., & Hanzálek, Z. (2019). Optimizing energy consumption of robotic cells by a Branch & Bound algorithm. *Computers and Operations Research.* https://doi.org/10.1016/j.cor.2018.09.012

Caesarendra, W., Wijaya, T., Pappachan, B. K., & Tjahjowidodo, T. (2019). Adaptation to industry 4.0 using machine learning and cloud computing to improve the conventional method of deburring in aerospace manufacturing industry. *Proceedings of 2019 International Conference on Information and Communication Technology and Systems, ICTS 2019*, 120–124. https://doi.org/10.1109/ICTS.2019.8850990

Erdős, G., Paniti, I., & Tipary, B. (2020). Transformation of robotic workcells to digital twins. *CIRP Annals*, 69(1), 149–152. https://doi.org/10.1016/j.cirp.2020.03.003

Gollmann, D., Gurikov, P., Isakov, A., Krotofil, M., Larsen, J., & Winnicki, A. (2015). Cyber-Physical Systems Security. *Proceedings of the 1st ACM workshop on cyber-physical system security - CPSS '15* (pp. 1–12). https://doi.org/10.1145/2732198.2732208

Grieves, M. (2015). Digital Twin: Manufacturing Excellence through Virtual Factory Replication. In *A Whitepaper*

Gurdal, O., Rae, B., Zonuzi, A., & Ozturk, E. (2019). Vision-assisted robotic finishing of friction stir-welded corner joints. *Procedia Manufacturing*. https://doi.org/10.1016/j.promfg.2020.02.013

Hansen, C., Öltjen, J., Meike, D., & Ortmaier, T. (2012). Enhanced approach for energy-efficient trajectory generation of industrial robots. *IEEE International Conference on Automation Science and Engineering*, 1–7. https://doi.org/10.1109/CoASE.2012.6386343

Humayed, A., Lin, J., Li, F., & Luo, B. (2017). Cyber-Physical Systems Security - A Survey. *IEEE Internet of Things Journal*, 4(6), 1802–1831. https://doi.org/10.1109/JIOT.2017.2703172

Ivan, M. A., Nicolescu, F. A., Aram, C. G., & Stan, L. (2015). Robotic deburring cell virtual prototyping. *Proceedings in Manufacturing Systems*, *10*(4), 183–188

Jayaweera, N., & Webb, P. (2010). Measurement assisted robotic edge deburring of aero engine components. WSEAS Transactions on Systems and Control

Kuss, A., Drust, M., & Verl, A. (2016). Detection of workpiece shape deviations for tool path adaptation in robotic deburring systems. *Procedia CIRP, 57,* 545–550. https://doi.org/10.1016/j.procir.2016.11.094.

Liao, L., Xi, F., Jeff, & Liu, K. (2008). Modeling and control of automated polishing/deburring process using a dual-purpose compliant toolhead. *International Journal of Machine Tools and Manufacture*, 48(12–13), 1454–1463. https://doi.org/10.1016/j.ijmachtools.2008.04.009

Lim, K. Y. H., Zheng, P., & Chen, C. H. (2019). A state-of-the-art survey of Digital Twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, 31(6), 1313–1337. https://doi.org/10.1007/s10845-019-01512-w

Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., & Deen, M. J. (2019). A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access*. https://doi.org/10.1109/ACCESS.2019.2909828.

Luo, W., Hu, T., Ye, Y., Zhang, C., & Wei, Y. (2020). A hybrid predictive maintenance approach for CNC machine tool driven by Digital Twin. *Robotics and Computer-Integrated Manufacturing*. https://doi.org/10.1016/j.rcim.2020.101974

Mourtzis, D., Vlachou, E., Dimitrakopoulos, G., & Zogopoulos, V. (2018). Cyber-physical systems and education 4.0–the teaching factory 4.0 concept. *Procedia Manufacturing*, *23*, 129–134. https://doi.org/10.1016/j.promfg.2018.04.005

Munteanu, A., Muradore, R., Merro, M., & Fiorini, P. (2018). On cyber-physical attacks in bilateral teleoperation systems: An experimental analysis. *Proceedings – 2018 IEEE Industrial Cyber-Physical Systems, ICPS 2018*, 159–166. https://doi.org/10.1109/ICPHYS.2018.8387653

Nicolescu, A. F., Stan, E. L., & Pupaza, C. (2019). E-Learning Platform for Robotic Appli—cations. *ICERI2019 Proceedings*. https://doi.org/10.21125/iceri.2019.1760

Paryanto, Brossog, M., Bornschlegl, M., & Franke, J. (2015). Reducing the energy consumption of industrial robots in manufacturing systems. *International Journal of Advanced Manufacturing Technology*, 78(5–8), 1315–1328. https://doi.org/10.1007/s00170-014-6737-z

Paryanto, Brossog, M., Kohl, J., Merhof, J., Spreng, S., & Franke, J. (2014). Energy consumption and dynamic behavior analysis of a six-axis industrial robot in an assembly system. *Procedia CIRP*, 23(C), 131–136. https://doi.org/10.1016/j.procir.2014.10.091

Pellicciari, M., Berselli, G., Leali, F., & Vergnano, A. (2013). A method for reducing the energy consumption of pick-and-place industrial robots. *Mechatronics*, 23(3), 326–334. https://doi.org/10.1016/j.mechatronics.2013.01.013

Priggemeyer, M., Losch, D., & Roßmann, J. (2018). Interactive calibration and visual programming of reconfigurable robotic workcells. *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, *2018-July*, 1396–1401. https://doi.org/10.1109/AIM.2018.8452707

Quarta, D., Pogliani, M., Polino, M., Maggi, F., Zanchettin, A. M., & Zanero, S. (2017). An experimental security analysis of an industrial robot controller. *Proceedings - IEEE symposium on security and privacy* (pp. 268–285). https://doi.org/10.1109/SP.2017.20

Ramis Ferrer, B., Muhammad, U., Mohammed, W., & Martínez Lastra, J. (2018). Implementing and visualizing ISO 22400 key performance indicators for monitoring discrete manufacturing systems. *Machines, 6*(3), 39. https://doi.org/10.3390/machines6030039.

Rivera, L. F., Jiménez, M., Angara, P., Villegas, N. M., Tamura, G., & Müller, H. A. (2019). Towards continuous monitoring in personalized healthcare through digital twins. *Proceedings of the 29th* annual international conference on computer science and software engineering, (pp. 329–335)

Schneider, U., Drust, M., Ansaloni, M., Lehmann, C., Pellicciari, M., Leali, F. … Verl, A. (2016). Improving robotic machining accuracy through experimental error investigation and modular compensation. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-014-6021-2

Stark, R., Kind, S., & Neumeyer, S. (2017). Innovations in digital modelling for next generation manufacturing system design. *CIRP Annals*, 66(1), 169–172. https://doi.org/10.1016/j.cirp.2017.04.045

Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital twins and cyber–physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. *Engineering, 5*(4), 653–661. https://doi.org/10.1016/j.eng.2019.01.014.

Tao, F., & Zhang, M. (2017). Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing. *IEEE Access*, 5, 20418–20427. https://doi.org/10.1109/ACCESS.2017.2756069

Tharma, R., Winter, R., & Eigner, M. (2018). An approach for the implementation of the digital twin in the automotive wiring harness field. *Proceedings of international design conference* (pp. 3023–3032). https://doi.org/10.21278/idc.2018.0188

Tomiyama, T., & Moyen, F. (2018). Resilient architecture for cyber-physical production systems. *CIRP Annals*, 67(1), 161–164. https://doi.org/10.1016/j.cirp.2018.04.021

Tong, X., Liu, Q., Pi, S., & Xiao, Y. (2019). Real-time machining data application and service based on IMT digital twin. *Journal of Intelligent Manufacturing*, 31(5), 1113–1132. https://doi.org/10.1007/s10845-019-01500-0

Tuegel, E. J., Ingraffea, A. R., Eason, T. G., & Spottswood, S. M. (2011). Reengineering aircraft structural life prediction using a Digital Twin. *International Journal of Aerospace Engineering*, 1–14. https://doi.org/10.1155/2011/154798

Uhlmann, E., Reinkober, S., & Hollerbach, T. (2016). Energy Efficient Usage of Industrial Robots for Machining Processes. *Procedia CIRP*, 48, 206–211. https://doi.org/10.1016/j.procir.2016.03.241

Uzun, M., Umut Demirezen, M., Koyuncu, E., & Inalhan, G. (2019). Design of a hybrid digital-twin flight performance model through machine learning. *2019 IEEE Aerospace conference* (pp. 1–14). https://doi.org/10.1109/AERO.2019.8741729

Vachalek, J., Bartalsky, L., Rovny, O., Sismisova, D., Morhac, M., & Loksik, M. (2017). The digital twin of an industrial production line within the industry 4.0 concept. *2017 21st International conference on process control (PC)* (pp. 258–262). https://doi.org/10.1109/PC.2017.7976223

Villagrossi, E., Pedrocchi, N., Beschi, M., & Molinari Tosatti, L. (2018). A human mimicking control strategy for robotic deburring of hard materials. *International Journal of Computer Integrated Manufacturing*, 31(9), 869–880. https://doi.org/10.1080/0951192X.2018.1447688

Wang, X. V., & Wang, L. (2021). A literature survey of the robotic technologies during the COVID-19 pandemic. *Journal of Manufacturing Systems*. https://doi.org/10.1016/j.jmsy.2021.02.005

Wang, J., Ye, L., Gao, R. X., Li, C., & Zhang, L. (2019). Digital Twin for rotating machinery fault diagnosis in smart manufacturing. *International Journal of Production Research*. https://doi.org/10.1080/00207543.2018.1552032

Wang, X., Wang, Y., & Xue, Y. (2006). Intelligent compliance control for robotic deburring using fuzzy logic. *2006 IEEE International Conference on Industrial Informatics, INDIN'06*. https://doi.org/10.1109/INDIN.2006.275723

Wu, M., Song, Z., & Moon, Y. B. (2017). Detecting cyber-physical attacks in CyberManufacturing systems with machine learning methods. *Journal of Intelligent Manufacturing*, 30(3), 1111–1123. https://doi.org/10.1007/s10845-017-1315-5

Xu, L., Da, & Duan, L. (2019). Big data for cyber physical systems in Industry 4.0: a survey. *Enterprise Information Systems*, 13(2), 148–169. https://doi.org/10.1080/17517575.2018.1442934

Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J. (2017). A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. *IEEE Access, 5*, 26901–26911. https://doi.org/10.1109/ACCESS.2017.2766453.

Zhuang, C., Liu, J., & Xiong, H. (2018). Digital twin-based smart production management and control framework for the complex product assembly shop-floor. *The International Journal of Advanced Manufacturing Technology*, 96(1–4), 1149–1163. https://doi.org/10.1007/s00170-018-1617-6