Deburring Using Robot Manipulators: A Review

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***Abstract*—Deburring of cast parts can be a very challenging task. Today, large burrs on large casting are mostly removed manually. Workers are exposed to hazardous working conditions through, among other things, high noise and vibration levels. Special purpose CNC-machines are available for deburring tasks, but they have a high investment cost that makes them unfit for high-mix low-volume processes. Deburring with robot manipulators are seen as a suitable and less expensive alternative, and have been in the focus of research topic for the last 50 years. Unfortunately, it has failed to move from research into industrial applications. One reason is the long system setup time that makes the cost of automatic deburring too high. This paper deals with the status and usage of robot manipulators in deburring applications with a focus on solutions for cast parts. The deburring pipeline and its components are investigated. There is a special focus on the solutions that lead to a more flexible and automatic deburring system by using sensors such as laser, vision and force control. The solutions are evaluated with regards to the current challenges with robotic deburring and what needs to be improved for robotic deburring to become available for high-mix low-volume processes.**

***Index Terms*—deburring, machining, robot manipulator, cast parts**

I. Introduction

Deburring of cast parts can be very challenging and large burrs on large casting are mostly removed manually with heavy-duty grinding disks or grinding cups [1]. Workers are exposed to high noise and vibration levels. It is also a very repetitive task that it is increasingly difficult to find willing and able workers to do.

In a CAD model, the geometries are clean and straight. The real geometry of the edges on the workpiece is however determined by the formation of burrs [2]. To achieve the desired geometry and functionality, the burrs often needs to be removed in time-consuming and expensive deburring processes. Burrs can prevent accurate mounting or assembly [1]. Many production methods can cause burrs to form such as drilling, turning, milling, cutting, punching and welding.

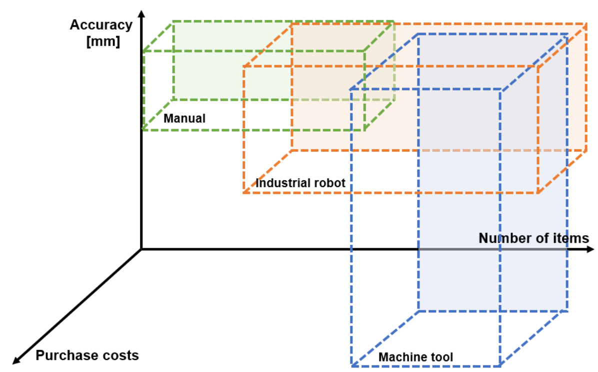

Fig. 1. Comparison between working accuracy, number of items in the batch, and purchase costs for the different deburring technologies (adapted from [3]).

A different type of burr is formed during casting where the burrs form on the separation plane between the two halves of a mold. They and can vary in shape and size depending on the (in)accuracy and wear of the mold and the process conditions.

Unfortunately, no single deburring operation can accomplish all required edge conditions on every edge for every burr without side effects. Therefore, several deburring methods are available. These vary depending on the type and size of the burr, as well as the size of the workpiece. Special purpose CNC machines are available to clean small to medium size casts, but these machines have high investment cost.

Industrial robots is an alternative to manual deburring and CNC machines. The main motivation for using robots instead of CNC machines is the cost. The price of a comparable robotic solution for machining is typically 1/5-1/3 of the cost of a CNC machine [4]. Despite the lower cost, only about 3% of industrial robots in industry are used for machining. The two main limitations with robot machining applications are the limited rigidity of the robots' tool-center-point (TCP) that impacts the machining accuracy and the long programming/setup time [5]. As a result, robotic cleaning of castings is currently limited to large production series. To enable robotic deburring for small and medium-sized enterprises (SMEs), the

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programming/setup time needs to be reduced. Figure 1 is an illustration, adapted from [3], that illustrates which deburring method that should be applied with regards to the required accuracy, production volume and the purchase/investment cost. If the production volume and the required accuracy is relatively low, manual deburring should be applied. If, on the other hand, the required accuracy and the production volume is high, and you have money to invest, CNC-machines should be applied. Today, robotic deburring is placed in between the two other methods. If the accuracy of the robotic system is improved and made more flexible and automated, in addition to the fact that the cost of robot manipulators is decreasing, industrial robots could replace both CNC-machines and manual labour in many applications.

This paper presents an overview of the robotic deburring pipeline. The state-of-the-art of each component of the pipeline is also presented. The current challenges to robot deburring is presented and how the various solutions tries to answer to the challenges. Finally, the future challenges that needs to be addressed for robotic deburring to become available for high-mix low-volume processes is discussed.

After this introductory section, the method of the literature search will be described in section II. Then, the deburring pipeline will be presented in section III. The two main steps of the deburring pipeline, namely planning and motion execution is described in section IV and V respectively. The different solutions and future challenges are discussed in section VI.

II. Method of literature search

The literature search was performed by searching using the controlled vocabulary in various databases. The search was executed in four different databases, namely Inspec, Compendex, IEEE Xplore and ScienceDirect. Since the controlled vocabulary varies between the databases, various vocabulary was used. All searches was limited to english language. For searching in Inspec and Compendex, the Engineering Village platform was used. The search was (”deburring” AND (“industrial robots” OR “robotics” OR “robots” OR “end effectors”) AND english language). This gave 222 results after removing duplicates. In IEEE Xplore, the used index term was ”deburring” with added index terms “industrial robots”, “industrial manipulators” and “robot programming”. This search gave 86 results. In Science Direct, the keyword ”robotic deburring” was used. This gave 75 results. In total, the search found 369 papers. After removing duplicates, 296 papers was remaining. A quick sorting was performed to remove papers based on access to the paper as well as relevance to the topic based on title and abstract. This reduced the number of papers to 109. All remaining papers were studied more thoroughly for relevance to the topic of this literature review.

III. Deburring pipeline

There are many different deburring processes, e.g. manual, mechanical, electrochemical and using thermal energy, [6]. Manual is the most common method because of its flexibility. Mechanical deburring is a process that mechanically removes

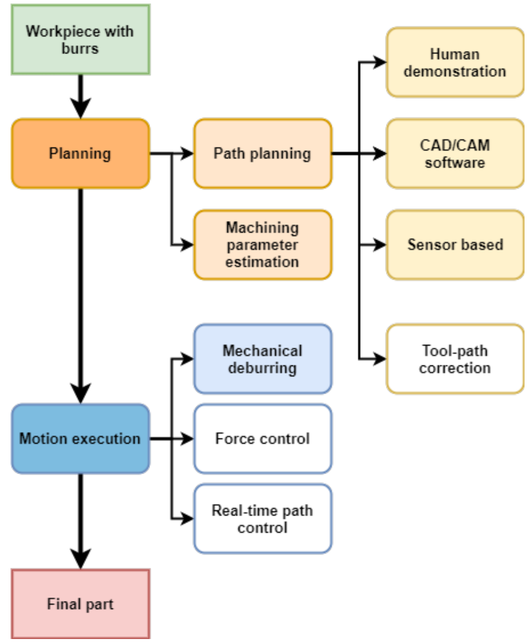

Fig. 2. Flowchart of the deburring pipeline.

the burr using tools like grinding disk or spindle. It is also the method of focus in this research. CNC-machines and robot manipulators combined with a deburring tool are the most common approach to mechanical deburring. The most appropriate approach can depend on required accuracy, batch size and burr size. CNC-machines are stiff and accurate, but also expensive and require that the machine is larger than the workpiece. The price of robot manipulators is 1/5-1/3 of the cost of a CNC-machine [4]. Robot manipulators also have a larger workspace meaning that the workpiece can be larger than the robot. The workspace can be further increased if the robot is placed on a mobile platform. The disadvantage is, however, that they are less stiff and accurate. With robots there is a question of whether the robot should hold the tool or the workpiece [7]. This question needs to be taken into account in the planning of the process.

The robotic deburring pipeline commonly consists of two main steps; planning and motion execution. The most important part of the planning step is the planning of the robot path. Other aspects such as tool-path correction and machining parameter estimation can also be a part of the planning process. The motion execution step is the step where physical part of the deburring process takes place. Within this step, mechanical deburring is the main component. Real-time feedback control can be added to improve the process often using force measurements. The different steps and component of the deburring pipeline is illustrated in Figure 2.

For a robot manipulator to perform a deburring process, a tool path is necessary. Within robotic deburring, there are three main approaches for generating a path. These are 1) Teaching trough human demonstration, 2) selecting the path based on the CAD model using CAD/CAM software, or 3) by automatically generating the path based on sensor input. In the method of teaching through human demonstration, an operator demonstrates where the robot will move and records the path. The CAD based approach includes using CAD/CAM software together with the CAD model of the part to generate the deburring path. This can be achieved by selecting the edges of the CAD model that needs to be deburred. The vision based approach is the least common compared to the two aforementioned methods. A vision system is used to recognise the edges of the workpiece. Like with the CAD/CAM method, the outline formed by the edges of the workpiece become the deburring path [8], [9].

A workpiece can have deformations due to the casting process or caused by clamping and gravity forces. The generated path then needs to be corrected based on these geometric variations and becomes a part of the planning process. First, a path is generated using one of the mentioned path planning methods. Then, a point cloud of the workpiece is generated using a 3D vision system. An algorithm is then used for calculating the transformation between the reference path and the workpiece [3], [10], [11].

The last component of the planning step is the machining parameter estimation. Burrs vary in size, especially burrs on cast parts. To improve the machining process, research has been done on optimizing machining parameters such as feed rate based on burr size [12], [13].

When all the planning is completed, the next step is the motion execution. As mentioned, the mechanical deburring is the main component here. This is the process that physically removes the burr. This can be completed by mounting a suitable machining tool on the robot and clamping the workpiece, or the other way around, and then follow the generated path from the previous step. If for example the burrs are large, the material is very hard or the accuracy requirements are very tight, it may be be necessary to use sensors follow the generated path. A common sensor is the force sensor. Force sensing in the robot control loop enables the robot to correct its motion e.g. slow down when a burr blocks the path. In applications where there are high accuracy requirements, laser systems can be used for real-time path tracking [14], [15].

IV. The Planning Process

This section will present the current status within the planning process of robotic deburring including the various solutions for path planning, tool path correction and machining parameter estimation.

A. Human demonstration

The most common approach to programming a robot is human demonstration [16]. This can is achieved by indirect demonstration which is guiding the robot manually using a teach pendant or a similar device. Sensors, such as force sensing, can be used to improve the interaction between the user and the environment [1]. It is also possible to move the manipulator manually and record the joint positions. This is called direct demonstration. Again, force sensors can be used to improve the demonstration process. One last form of demonstration is non-interactive where the robot is not used during the demonstration. One example is to use vision systems to analyze a demonstration directly from an image [1].

If the deburring path is curved, it must usually be approximated by many straight line segments, meaning that lots of points have to be programmed [17]. The programming can be very time consuming and the operator must be experienced to determine the necessary density of the points along the path.

A method combining human demonstration and vision is drawing. The operator ”demonstrates” the path by drawing the deburring path directly on the workpiece. Vision system is then used for digitizing the path. Examples of using drawing for deburring is presented in [18] and [19] which is further explained in section IV-C.

B. CAD/CAM software

Computer Aided Design (CAD) software is commonly used for designing the part to be manufactured while Computer Aided Manufacturing (CAM) software is used for planning the machining process, especially the tool path. There exist a vast selection of CAM software such as Solidworks CAM, by Solidworks [20], and NX CAM, by Siemens [21]. The tool path can be planned, generated and simulated in the CAM software. Output of the system is commonly a type of numerical control (NC)-code, for example G-code, but robot-specific-language is also possible. If the output is robot-specific-language, the CAM software has to compile the program into robot language [5]. The quality of the robot program then strongly depends on the quality of the post-processor implemented in the CAM software. To avoid the post-processor ”black-box”, robot control (RC) and CNC should be combined. RC has the possibility to check the robot trajectory’s feasibility as well as collision and singularity avoidance. KUKA is one of few manufacturers providing an integrated NC Kernel [5]. An RC software that is vendor independent is RoboDK which is an offline programming and 3D simulation of industrial robots [22]. It is also integrated with Autodesk Inventor. Inventor is a CAD/CAM software for 3D mechanical design, simulation, visualization and documentation [23].

C. Sensor-based path generation

To compliment CAD-based planning, or as a standalone solution, sensors can be used for generating the deburring path.

In [8], a vision-assisted robot offline programming system has been developed. The edges of the workpiece used for testing are all straight. The system recognise the straight lines in the image taken with a 2D vision camera using Hough transformation. An Off-Line programming (OLP) system transforms the straight lines into a path. Figure 3 shows the edges of the workpiece in red. The white lines shows the path generated using Hough transform that straightens the path, particularly in the corners. A similar solution is presented

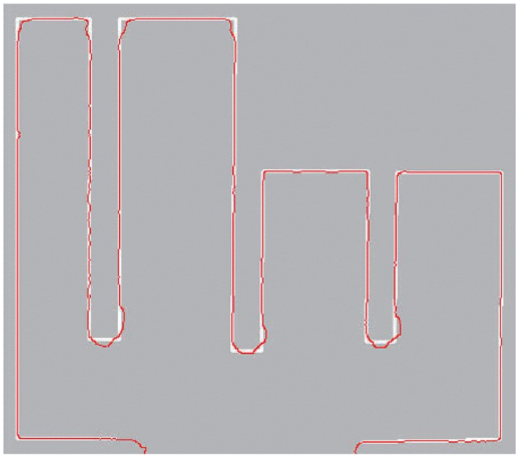

Fig. 3. The image of comparison between edges and lines detection. From [8].

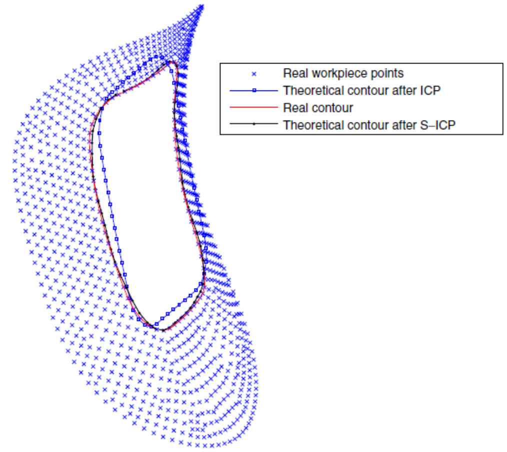

Fig. 4. Registration of a porthole with ICP and S-ICP. From [10]:

in [9]. Again, a camera is used for detecting the edges that are used for generating the path.

Reference [19] propose a deburring method that combines vision, CAD and human demonstration. The methodology is not 100% automatic by purpose to take advantage of the expertise of the worker to identify the locations of area to be modified. First, the deburring path is drawn with a pen on the workpiece by the operator. To digitize the path an image is taken of the path on the workpiece and the path is found in 2D (x and y coordinates) using the Canny edge algorithm. To find the 3D coordinates of the path, the 2D coordinates (x and y) of the path is placed together with the CAD model. The z-value is set to be the value of where the $x - y$ coordinate intersects the surface of the CAD model. The digitized version of the drawn path is stored and used for deburring. A similar solution is presented in [18]. First, a path is drawn on the workpiece. Then, the robot, with an eye-in-hand camera, follows and records the 2D path by moving in a zig-zag pattern. To record the z-coordinate, the robot also holds a tool that is kept in constant contact with the surface using force control. The path is recorded and smoothed to obtain a final tool path.

D. Tool-path correction

A workpiece can have deformations due to the casting process or due to clamping and gravity forces. These deformations are not negligible and should be taken into account. One solution is to find the transformation between the theoretical 3D model and the physical workpiece. This can be achieved by comparing a point cloud of a CAD model with the measurements given by a 3D measurement device [10]. The transformation between the two point clouds is calculated using registration algorithms. If the point clouds are not roughly aligned, the transformation of a rough alignment needs to be found first. Then a more fine tuned registration algorithm can calculate the final transformation. Once the transformation between the two point clouds is found, it can be used to correct a reference robot trajectory.

In [10], Iterative Closest Point (ICP) and a variation of the same algorithm, namely Subdivision-ICP (S-ICP), are tested and compared. The method is based on the assumption that the parts are rougly aligned. Figure 4, taken from Figure 6 in [10], shows the registration of a porthole together with the theoretical contour after both ICP and S-ICP as well as the real contour. It shows that the S-ICP algorithm manages to transform the tool path to the real contour.

Similar solutions to the method presented above is presented in [11] and [3]. In [11], the first step is to teach by demonstration a robot trajectory on a reference workpiece that has been manually deburred. The following steps are similar to the aforementioned one. The main difference is that a scan of the reference workpiece is used instead of a CAD model as in the previous method. The ICP algorithm is used for calculating the transformation needed to transform the generated robot trajectory. The method is based on the assumption that the parts are roughly alignes like in [10]. In [3], the deburring path is demonstrated on a reference workpiece, here called master workpiece (MWP). For computing the deformation, some control points are taught in an area where there are expected to be no burrs. The MWP is scanned and stored as a reference point cloud. Then, a new workpiece, called slave workpiece (SWP) is scanned. The rigid transform is calculated using the ICP algorithm. The taught control points are compared and used for calculating the local deformation. The deburring path is then corrected for based on the translation, rotation and deformation.

Another approach for correcting the tool path based on deformations is presented in [24]. It is argued that the method used in [10] is too complex and that ”problems will arise in industrial applications with respect to fast and robust integration”. The presented method in [24] consists of three main steps. In the first step, a set of reference CAD models is generated based on the nominal CAD model and its given tolerances. These are meant to represent the possible deformations the final workpiece can have. In the second step, the workpiece is measured using a vision system and a point cloud is generated. This point cloud is then compared to the set of reference CAD models to find the most similar one. In the third and final step, the tool path is generated based on the identified CAD model using traditional CAD/CAM software.

All the above-mentioned solutions use vision for correcting the tool path. Reference [25] presents a method that corrects the path based on teaching points. A tool path is first generated using CAM software with a CAD model. Then a set of direct teaching points are manually selected, which are the minimum set of points to capture the shape of the workpiece. Finally, the transformation between the tool path and the teaching points is calculated and the tool path is corrected for.

E. Machining parameter estimation

There are various machining parameters that affect the end result such as spindle speed, feed rate, force and depth of cut. The current practice is to perform the process verification and fine-tuning of parameters step by step and manually, [7]. In [26], the TOPSIS method has been used to optimize parameters for robotic deburring. Parameters such as diameter of grinding wheel, speed of grinding wheel, feed rate, force and surface roughness has been taken into account. Results show that feed rate is the most influencing parameter impacting the force and surface roughness. Research has been done to optimize the feed rate automatically. Reference [12] and [13] present solutions that tries to adjust the feed rate based on estimates of the burr size. In [12], the mean and standard deviation of the burr height is calculated based on several images of the workpiece. The scope of the burr height is split into levels with regards to the mean value. The feed rate is assigned according to the burr level. The larger the burr the lower the feed rate. A similar solution is presented in [13]. The burr size is estimated using a local deformable template matching algorithm. Thresholds of the burr size is used to decide the corresponding feed rate. It is stated that the deburring time is reduced by 3.94%.

V. The motion execution process

The motion execution process consists of mechanical deburring, force control and real-time path control. This section considers the solutions in force control and real-time path control using vision systems. Mechanical deburring is a field on its own and is not considered in this paper.

A. Force control

The Control of an interaction between a robot and a workpiece is known as *force control*. High-stiffness machines such as CNC-machines control only position and assume that contact forces are *small*. A high precision and high stiffness CNC machine is expensive. By controlling the interaction forces directly, less expensive and more flexible equipment could be used. Force control has failed to move from research into industrial application. A major reason is that the cost savings does not warrant the increase in complexity [27]. Recent low-cost robots such as the UR10e and Franka Emika have built-in force sensing which make the cost/benefit ratio attractive. The cost of equipment is low, whereas the upkeep and development cost is still high.

The two force control strategies relevant for deburring are:
1) **Impedance/Admittance control**, where the end-effector is controlled to have a mass-spring-damper behaviour [28]. The effect is the same as mounting a compliant spring between the end-effector of the robot and the tool. In a deburring operation, the robot will move its tool along a nominal path around the object, and will deflect when the tool hits a burr. Several repetitions will need to be done until no deviations are measured [29].
2) **Hybrid force-motion control** where contact forces are controlled explicitly along certain axes. In deburring, the position/velocity controlled axes would be along a path around the surface of the object. The force-controlled axis could be normal to the path [30].

High-stiffness interaction such as metal-on-metal is problematic in force control [7]. In a high stiffness collision, e.g. when the spindle first meets the part - an impulse spike is measured on the force sensor. The force impulse propagates through the robot control loop, and often result in a shaking robot. The easiest fix for this is to reduce the impacts forces by reducing the speed of the robot, at the cost of increased cycle time. Therefore, it is of interest to develop a control method or hardware mechanism to limit the impact force even if the approach speed is high. Other fixes include: 1) Minimizing time-delay in the force control loop. 2) Mechanical compliance such as springs, or the use of compliant, backdrivable robot arms.

B. On-line path correction - Vision

Some parts have very tight tolerances and therefore requires very high accuracy. One example is the aerospace industry which typically has very tight tolerances. The stiffness of the robot manipulator is key when it comes to the accuracy of the system. The limited static and dynamic stiffness of both robot joints and links results in limited rigidity of the robot TCP (tool center point). This impacts the machining accuracy [5]. To improve the accuracy when using robot manipulators for deburring, one solution is to introduce sensors for real-time control. A low-accuracy robot can achieve high-accuracy by using sensor-feebcack control. Reference [14] present a method for real-time pose control using a laser tracker system. The target position of the tool is compared with the actual position, measured by the laser tracker system, to calculate the positional error. This error is used in a control loop to correct for robot position. In reference [15], a system for real-time path correction using a cost-effective laser triangulation sensor is presented. The application is an adhesive one and not machining, but the method is applicable for both. An reference path is generated using offline CAD/CAM software. The laser system is used to measure the actual position of the TCP and this is compared to the associated point on the reference path to calculate the positional error. This error is fed in to a path adaption algorithm.

VI. Discussion and future challenges

Manual deburring is an hazardous task that can and should be automated. Despite this, manual deburring is still very common in high-mix low-volume processes. This is because the total cost and complexity of automating the process is too high. To address this problem, the state-of-the-art of robotic deburring has been investigated and presented. When evaluating the various solutions, it is useful to consider the current challenges to robotic deburring. Reference [7] and [5] both present a list of challenges that needs to be addressed. Below is a list that combines the challenges from the two references.

1) Improved setup/programming method
2) Limit the impact force
3) Process parameter adaptation algorithm
4) User friendly and maintainable system not only by experts
5) Burr position and dimension estimation for improved process
6) System for improved accuracy to meet industry demands

The first challenge, improved setup/programming method, can be addressed in many ways. A large part of this problem is the process of generating a deburring path. This needs to be done effectively, especially if there is a high-mix of parts. Human demonstration is the most common approach for generating the path. It is an intuitive method where the path in demonstrated directly with the robot manipulator. The downside with this method is that programming can be very time consuming, especially for complex parts. An alternative to human demonstration is to use CAM software, where the CAD model is used to generate the path. If the user is familiar with the software, the process of generating the path is quick. A possible disadvantage with this method is that the CAD model of the workpiece is required, but almost all parts that are made today starts with a CAD model.
Once the reference path is generated, it has to be transformed to fit for every workpiece. Geometric variations between every workpiece can occur due to deformations and clamping. These variations needs to be taken into account to avoid removing too much or too little material. This can be solved by correcting the tool-path using the transformation between the workpiece and the reference part. The alignment of the workpiece and reference point cloud can be challenging if there are large burrs on the workpiece as on cast parts.

Tool-path correction is not necessary for the last method of path generation, vision assisted path generation. The method is based on the assumption that the burrs are located along the edges of the outline of the workpiece. The assumption is valid for most parts, including cast parts. If the assumption is met, the deburring path can be generated automatically by setting the path equal to the edges along the outline of the workpiece. There are still challenges when it comes to more complex parts. Until now, only simple geometries with straight lines have been solved.

The first challenge glides into challenge 3 and 5 also. Process parameter estimation can both be a part of the planning, setup, and the on-line process monitoring. Challenge 5, burr position and dimension estimation, can affect both the path planning and the process parameters, depending on how the problem is solved. Process parameters are to a large extent verified and fine tuned step by step and manually today. A process parameter estimation and adaptation algorithm could overcome this manual process. There has been some research on estimating the feed rate. Although in many cases burrs are characterized by relatively small size and low variability, the ones occurring in the casting process might be large and non-uniform. By estimating the size of the burrs using a vision system, the feed rate can be adjusted automatically. Reference [12] and [13] has realised this. Both solutions use 2D vision system and therefore only estimate the height of the burr. Another interesting aspect would be to consider the thickness of the burr as well.

Challenge 6 is concerning the accuracy of the robotic deburring system. It is a known challenge that robots have a low stiffness that results in lower accuracy than CNC-machines. The accuracy can be improved by upgrading to a stiffer robot, or by including sensors. In reference [14] and [15], a laser tracking system is used to improve the positional accuracy of the robot. Force-controlled robots can improve the machining accuracy, but are challenging to implement in a fast and robust way.

To limit the impact force, which is challenge 2, was mentioned in section V-A. It is of interest to develop a control method to limit the impact force so it does not propagate through the control loop. This can be achieved by reducing the approach speed of the robot, but this results in an increased cycle time. Other possible fixes include minimizing time-delay in the force control loop or by adding mechanical compliance.

The last challenge that have not yet been discussed is challenge 4, that the system is user friendly and maintainable by operators and not only experts. This has also been brought up as a key factor in the authors' conversations with the industry. It is challenging to say what makes a system user friendly and maintainable. Deburring is a complex process and it is not trivial to program a robot manipulator either. It is therefore impossible to not require some level of expertise to use the system. There should be made an effort into making the system as intuitive as possible and not make it behave like a "black box". The input and output of the system should be clear as well as how they are handled. It should also be easily configurable in a way that an operator can make small and rapid modifications to adjust the process.

2D vision has been used for path generation for simple geometries. The advantage with this method is that it requires little or no human interaction. The method is promising, but it needs to be further developed for it to work on more complex geometries. One option is to combine 3D vision and the CAD model. The burrs can be detected by comparing the recorded point cloud of the workpiece with the CAD model that works as reference. A path that removes the detected burrs can

then be generated. There is, however, a challenge with the alignment of the point cloud and the CAD model. If there are large burrs and deformations on the workpiece and the position and orientation is unknown, the registration can be very complex.
Once the burrs are detected using 3D vision and CAD model, it is possible to use the same data to estimate the burr size. The estimated burr size can then be used to further develop the method of estimating the process parameters such as feed rate.

Despite there being many solutions to the different aspects of the deburring pipeline, there is no solution that combines them into one. This means that the different processes of the pipeline are handled separately with little or no communication. Future work could be done in combining some of the processes into one system such as the planning process. As described above, many of the challenges with the planning aspect of the robotic deburring are connected, such as improved setup/programming, parameter estimation and burr size and position estimation. By combining the processes, the pipeline will be greatly simplified, also making the system more user friendly.

References

[1] Erwin Aertbeliën, "Development and acquisition of skills for deburring with kinematically redundant robots," Ph.D. dissertation, Catholic University of Leuven, 2009.

[2] J. C. Aurich, D. Dornfeld, P. J. Arrazola, V. Franke, L. Leitz, and S. Min, "Burrs-Analysis, control and removal," *CIRP Annals - Manufacturing Technology*, vol. 58, no. 2, pp. 519–542, 2009.

[3] E. Villagrossi, C. Cenati, N. Pedrocchi, M. Beschi, and L. Molinari Tosatti, "Flexible robot-based cast iron deburring cell for small batch production using single-point laser sensor," *International Journal of Advanced Manufacturing Technology*, vol. 92, no. 1-4, pp. 1425–1438, sep 2017.

[4] A. Brunete, E. Gambao, J. Koskinen, T. Heikkilä, K. B. Kaldestad, I. Tyapin, G. Hovland, D. Surdilovic, M. Hernando, A. Bottero, and S. Anton, "Hard material small-batch industrial machining robot," *Robotics and Computer-Integrated Manufacturing*, vol. 54, pp. 185–199, dec 2017.

[5] A. Verl, A. Valente, S. Melkote, C. Brecher, E. Ozturk, and L. T. Tunc, "Robots in machining," *CIRP Annals*, 2019.

[6] L. K. Gillespie, *Deburring and edge finishing handbook*. Society of Manufacturing Engineers, 1999.

[7] Y. C. Sun and C. Y. Lai, "Robotic finishing," in *HandBook of Manufacturing Engineering and Technology*. Springer-Verlag London Ltd, 2015, pp. 2445–2468.

[8] Z. Lai, R. Xiong, H. Wu, and Y. Guan, "Integration of Visual Information and Robot Offline Programming System for Improving Automatic Deburring Process," in *2018 IEEE International Conference on Robotics and Biomimetics, ROBIO 2018*. Institute of Electrical and Electronics Engineers Inc., mar 2018, pp. 1132–1137.

[9] F. Leo Princely and T. Selvaraj, "Vision assisted robotic deburring of edge burrs in cast parts," in *Procedia Engineering*, vol. 97, 2014, pp. 1906–1914.

[10] R. Béarée, J. Y. Dieulot, and P. Rabaté, "An innovative subdivision-ICP registration method for tool-path correction applied to deformed aircraft parts machining," *International Journal of Advanced Manufacturing Technology*, vol. 53, no. 5-8, pp. 463–471, mar 2011. [Online]. Available: http://link.springer.com/10.1007/s00170-010-2875-0

[11] H. Kosler, U. Pavlovčič, M. Jezeršek, and J. Možina, "Adaptive Robotic Deburring of Die-Cast Parts with Position and Orientation Measurements Using a 3D Laser-Triangulation Sensor," *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 62, no. 4, p. 207, apr 2016. [Online]. Available: http://www.sv-jme.eu/article/adaptive-robotic-deburring-of-die-cast-parts-with-position-and-orientation-measurements-using-a-3d-laser-triangulation-sensor/

[12] C. Y. Lai, D. E. Villacis Chavez, and S. Ding, "Transformable parallel-serial manipulator for robotic machining," *The International Journal of Advanced Manufacturing Technology*, vol. 97, no. 5-8, pp. 2987–2996, jul 2018. [Online]. Available: http://link.springer.com/10.1007/s00170-018-2170-z

[13] R. Xiong, Z. Lai, Y. Guan, Y. Yang, and C. Cai, "Local Deformable Template Matching in Robotic Deburring," in *2018 IEEE International Conference on Robotics and Biomimetics, ROBIO 2018*. IEEE, dec 2018, pp. 401–407. [Online]. Available: https://ieeexplore.ieee.org/document/8665325/

[14] C. Moeller, H. C. Schmidt, P. Koch, C. Boehlmann, S. Kothe, J. Wollnack, W. Hintze, C. . Moeller, C. Schmidt, H. Koch, and P. Boehlmann, "Real Time Pose Control of an Industrial Robotic System for Machining of Large Scale Components in Aerospace Industry Using Laser Tracker System "Real Time Pose Control of an Industrial Robotic System for Machining of Large Scale Components in Aerospace Industry Using Laser Tracker System," *SAE Int. J. Aerosp*, vol. 10, no. 2, p. 2017, 2017.

[15] N. H. Shah, S. Subramanian, and J. Wollnack, "Real-Time Path Correction of an Industrial Robot for Adhesive Application on Composite Structures," *SAE Technical Papers*, vol. 2018-April, pp. 1–9, 2018.

[16] A. Skoglund, "Programming by demonstration of robot manipulators," Ph.D. dissertation, Örebro universitet, 2009.

[17] T. Thomessen, O. J. Elle, J. Lund Larsen, T. Andersen, J. E. Pedersen, and T. K. Lien, "Automatic programming of grinding robot," *Modeling, Identification and Control: A Norwegian Research Bulletin*, vol. 14, no. 2, pp. 93–105, 1993. [Online]. Available: http://www.mic-journal.no/ABS/MIC-1993-2-4.asp

[18] H. Zhang, H. Chen, N. Xi, G. Zhang, and J. He, "On-line path generation for robotic deburring of cast aluminum wheels," in *IEEE International Conference on Intelligent Robots and Systems*, 2006, pp. 2400–2405.

[19] B. Solvang, G. Sziebig, and P. Korondi, "Vision based robot programming," in *Proceedings of 2008 IEEE International Conference on Networking, Sensing and Control, ICNSC*, 2008, pp. 949–954.

[20] Dassault Systèmes SolidWorks Corpration, "Solidworks CAM," https://www.solidworks.com/product/solidworks-cam, 2020, [Online; accessed 30-March-2020].

[21] Siemens Industry Software Inc., "NX for Manufacturing," https://www.plm.automation.siemens.com/global/en/products/nx/nx-for-manufacturing.html, 2020, [Online; accessed 30-March-2020].

[22] RoboDK Inc, "RoboDK," https://robodk.com/, 2020, [Online; accessed 31-January-2020].

[23] Autodesk Inc, "Inventor - Professional-grade 3D CAD software for product design and engineering," https://www.autodesk.com/products/inventor/overview, 2020, [Online; accessed 31-January-2020].

[24] A. Kuss, M. Drust, and A. Verl, "Detection of Workpiece Shape Deviations for Tool Path Adaptation in Robotic Deburring Systems," *Procedia CIRP*, vol. 57, pp. 545–550, 2016. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2212827116312483

[25] H. C. Song, B. S. Kim, and J. B. Song, "Tool path generation based on matching between teaching points and CAD model for robotic deburring," in *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, 2012, pp. 890–895.

[26] F. Leo Princely, P. Senthil, and T. Selvaraj, "Application of TOPSIS method for optimization of process parameters in robotic deburring," *Materials Today: Proceedings*, oct 2019.

[27] M. Jonsson, A. Stolt, A. Robertsson, S. von Gegerfelt, and K. Nilsson, "On force control for assembly and deburring of castings," *Production Engineering*, vol. 7, no. 4, pp. 351–360, jul 2013. [Online]. Available: http://link.springer.com/10.1007/s11740-013-0459-1

[28] N. Hogan, "Impedance control of industrial robots," *Robotics and Computer-Integrated Manufacturing*, vol. 1, no. 1, pp. 97–113, 1984.

[29] E. Villagrossi, N. Pedrocchi, M. Beschi, and L. Molinari Tosatti, "A human mimicking control strategy for robotic deburring of hard materials," *International Journal of Computer Integrated Manufacturing*, vol. 31, no. 9, pp. 869–880, 2018.

[30] J. N. Pires, J. Ramming, S. Rauch, and R. Araújo, "Force/torque sensing applied to industrial robotic deburring," *Sensor Review*, 2002.