Robotic Polishing of the Meat Grinder Blade under Path Planning and Controlled Force

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Abstract. In recent years, industrial robots have been widely used in many applications such as assembling, stacking, welding, spraying and others. Whereas, the surface grinding and polishing are the applications which are still required a lot of improvement especially for the curved and free form surfaces. Most commonly used articulated robots are suitable candidates for such surfaces because its end effector can provide orientations required for polishing of the free from surfaces. Besides the reachability, tool path planning and the contact force between polishing tool and surface are other two important factors which required proper consideration. This paper presents the robotic polishing of the meat grinder blade under suitable path planning and controlled force. Computer-Aided Manufacturing (CAM) software Mastercam is used to achieve the trajectory path of the robot during the polishing process. Experiments are conducted to prove the adopted methodology.

Keywords: Surface polishing; Path planning; Force control; Free form surface; Computer-aided manufacturing.

1. Introduction
Cumulative demand for the cost-effective production processes and less human interaction in the manufacturing industries imposed new challenges in the automation technology. To automate the manufacturing process many industrial robots are used in plenty of applications like welding, painting, assembling and drilling [1-4]. Grinding and polishing are the last processes of many industrial products, which requires up to 30\% of the total processing cost [5, 6]. Many industries still depend on the skills of the polishing workers for this last processing step. Consequently, there is a high demand to automate the grinding and polishing process.

However, industrial robots are introduced in the surface polishing still lots of work is needed in this area to mature this application for free form surfaces. For the simple plain surfaces, it is comparatively easy to achieve good polishing results and maintain the contact force by just alignment of the tools by using simple machines. In case of parts with complex curved surfaces, many practical factors are needed to be considered such as curvature of the surface and selection of tool which can cover the whole polishing area. Different shape, material and the required surface quality needed separate polishing tools and parameters. Numbers of attempts are done for the improvement of the polishing process for the curved surfaces by the implementation of the new tool design, better planning of the...
polishing tool trajectory, control the interaction between the polishing tool and the surface [7-12]. In the field of automation today, the use of computer-aided manufacturing (CAM) software is increasing and has great advantages in trajectory planning. It reduces the process implementation time and increases the proficiency of the process. Therefore CAM plays an important role in the development of robot polishing.

This paper presents the robotic polishing of the meat grinder blade using a flexible six-axis industrial robot with efficient path planning under controlled force. A stable fixture holding the workpiece is used against a rotating polishing tool attached to the force sensor. CAM software Mastercam is used to achieve the trajectory path of the robot during the polishing process. The presented approach is simple in implementation and can improve the productivity of the polishing process in free form surfaces.

2. The System Overview

2.1. Workpiece and fixture

Figure 1 shows the meat grinder blade used in robotic polishing. It is small in size and has four blades. The maximum diameter at rotation of the blade is 60 mm and the height is 11 mm. The material used in the blade is stainless steel.

![Figure 1. Meat grinder blade: (A) top view, and (B) isometric view.](image)

A specific purpose fixture is designed to strongly hold the workpiece during the polishing process. Figure 2 shows this fixture for the blade which has two parts connected by screws. Part one is the base of the fixture which is attached with the robot last link and second part separates the base and the workpiece.

![Figure 2. Fixture designed to hold meat grinder blade during polishing.](image)

2.2. Force control system

In order to control the contact force between tool and workpiece surface, a separate force feedback system setup is used. The correct amount of the contact force is better for the productivity and quality of the polishing force. Figure 3 shows the Active Contact Flange ACF110-01 by Ferrobotic which is used in this work. It can control the force and position of the end effector based on a feedback loop. It has 1.2 Kg dead weight and eligible to control the force between 1 N to 100 N.
Figure 3. Active contact flange (ACF 110-04) attached with the motor holding polishing tool. In the presented work, polishing tool driven by the variable speed motor attached with the force sensor is fixed in front of the robot. This arrangement provides a normal contact force on the polishing surface throughout the trajectory. This closed-loop force sensor system has its separate controller and software.

2.3. Tool path planning

Tool path planning is one of the important factors in robotic polishing of the free form surfaces. Meat grinder blade has four blades and every blade is divided into 2 part surfaces. The actual picture of the blade is shown below 4 picture.

Figure 4. Unpolished Meat grinder blade.

Most commonly used tool path pattern is scanning path which is used to cover the polishing area. Scanning path pattern has two types which are S and Z scanning pattern as shown in Figure 5. In S pattern, the tool direction change alternative whereas in Z pattern tool maintains its direction throughout the path. For the meat grinder blade polishing S scanning pattern is selected. The distance (u) between the consecutive lines controls the density of the pattern and its productivity.

Figure 5. Scanning path pattern: (a) S pattern, and (b) Z pattern.

The number of scanning lines (N) on the surface is the number of tool paths scan required to cover the polishing surface. It follows the formula as
Where is the effective polishing width of the tool and is the total width of the polishing surface. The effective cutting width is related to the material of the grinding tool, the contact angle between the tool and the part, and the contact force. The width of the surface depends on the actual shape of the surface and the grinding direction selected.

Figure 6 shows the implemented S scanning pattern on the workpiece and the sequence of the part surface being polished. The selection of the part number is adopted by considering the joint limit of the robot last link J6 (+360 < J6 < -360). Path density can be adjusted according to the effective area of the tool. For the surfaces with high curvature, it needed high path density.

![Figure 6. Fixture designed for the meat grinder blade.](image)

Another important consideration in the tool path planning is the selection of the tool centre point. It is the point on the tool that is the reference for all the tool path points. In case of curved surfaces or surface polishing area near to the corner of the workpieces, tools can meet interference with the rest of the structure or surface. Sometimes to avoid the interference or to reach the corner of the surface, the tool centre point is selected near the edge of the tool but still, there are chances for the surface interference as shown in Figure 7 (a). This interference is damaging for the tool and workpiece and affects the process quality. To avoid this clash an additional angle is added to the tool which can prevent interference as shown in Figure 7 (b).

![Figure 7. Polishing tool with center near edge on curve surface: (a) with interference, and (b) no interference.](image)
interference. Figure 8 shows the work flow chat of the tool path planning for the robotic polishing of the grinder blade. It consists of the CAD model generation, tool path planning, generation and implementation of the program on the robot. Polishing parameters such as tool rotation speed, contact force and the path density can be adjusted to achieve the final results.

![Flow chart for robotic polishing](image)

**Figure 8.** Flow chart for the robotic polishing of the workpiece by using CAM software. Through computer software (CAD, CAM), the model was built and the path was planned to simplify the polishing of the original complex robot, and the actual effect was fed back to the experimenters to improve the polishing effect continuously.

Two tools with different material are used in the polishing of the meat grinder blade. Figure 9 (a) shows the sesame sand grinding tool (Tool A) which comparatively hard on the polishing surfaces and it has 180 grit #. Another used tool (Tool B) in figure 9 (b) is a little soft due to the yellow pad it has and able to change the grit # of the sandpaper required.

![Polishing tool](image)

**Figure 9.** Polishing tool used for meat grinding blade: (a) sesame sand grinding tool, and (b) small tool with sand paper.

3. Results and Discussion

3.1. Experimental setup

The robotic polishing experimental setup used in this work consists of an articulated robot ABB IRB 1200 robot with IRC5 controller, a force control system with separate setup and a rotatory polishing tool attached with the force sensor places in front of the robot as shown in Figure 10. As compared to the weight and size of the workpiece and fixture used, payload (7 Kg) of the ABB IRB 1200 robot is enough to support during polishing. Additionally, it can handle the polishing force between the tool and workpiece surface. Tool path planning and the conversion of trajectory into the robot joints values is done by the simulation software Robotmaster.
Figure 10. Experimental setup for the robotic polishing of the meat grinder blade. Ideally, in the grinding process, the grinding tool should be normal to the curve polishing surface for maximum surface contact. As discussed in tool path planning, an extra little angle is added to the tool orientation to avoid the interference. This addition angle only applied to the surfaces 5, 6, 7 and 8 because only these have interference problem. Figure 11 (a) shows the meat grinder blade before polishing which has a very rough and hard surface. It required multiple polishing stages. Figure 11 (b) shows very deep grinding on the blade surface because sesame grinding tool is very rigid. In polishing, it is always required that the surface finish is achieved by less material removal. To accomplish this requirement another tool with an additional soft pad in it is used. Figure 11 (c) shows the blade which treated with a tool having a soft pad and 180# sandpaper on it. It has a much better impact and did not show deep grinding on the surface.

Figure 11. Meat grinder blade: (a) before polishing, (b) after using tool A, and (c) after using tool B. Beside additional angle to the tool orientation and the tool types, another important useful polishing parameter is the density of the scanning path. Figure 12 (a) shows the blade after polishing using tool B with low path density. Compared with the effective area of the tool this path density is little less so path density of the tool is increased. Little high density which has a better impact on the surface. Very high path density can provide better surface but it can increase the material removal which is not desired. Additionally, the increase in path density will increase processing time and will not be economical for the production process.

Finally, after polishing of the workpiece using tool B with P180 grit sandpaper as a first stage, the workpiece is treated with P320 grit sandpaper for the second stage with same density achieved in the last step. Figure 12 shows the finally polished meat grinder blade after the polishing process with two stages. Table I shows some important parameters of the robotic polishing system for the meat grinder blade. It includes robot payload, selected tools, contact force, tool rotation speed, tool grit number and feed rate.
Figure 12. Meat grinder blade after treatment with P320 grit sand paper as second polishing stage.

Table 1. Some important parameters

| Parameters                              | Values  |
|----------------------------------------|---------|
| Payload of the robot                    | 7 Kg    |
| Sesame sand grinding tool (Tool A)      | P180    |
| Tool with sand paper (Tool B)           | P180, P320 |
| Constant sensor force                   | 5 N     |
| Tool rotation speed                     | 2000 r/min |
| Feed rate                              | 10 mm/s |

It was found in the experiment that the contact force should not be too large, which would cause the cutting amount to be too large, unable to meet the actual requirements, the force effect of 5N is the best, rough grinding should cooperate with the tool rotation speed is small, the fine grinding speed is large, the experiment to choose the intermediate value to adapt to the fine grinding and rough grinding two conditions., the best Feed rate is 10 mm/s.

4. Conclusion

For the curved and free form surfaces, polishing is a difficult multistage process. This paper explains the method for the robotics polishing of the meat grinder blade under tool path planning and force control. A CAD model-based path planning for the polishing of the meat grinder blade is adopted. Scanning path pattern with S scanning pattern is implemented with CAM software Mastercam. Effective force control system ACF is used for the force and position control during planned path for the polishing the curve surface. This two-stage robotics polishing treated workpiece with grit # 180 and 320 in these stages. Effect of different path densities and tool types is also presented and discussed. Final product with required quality on the meat grinder blade surface is achieved within two polishing cycles. The contact force of 5 N, the feed rate of 10 mm/s and the tool rotation speed of 3000 rpm is used as the polishing parameters. Experimental results for the meat grinder blade has approved this method and indicated some avenues of future work.

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