ABCM Symposium Series in Mechatronics - Vol. 1 - pp.124-133

A NEW APPROACH FOR TOOL PATH CONTROL IN ROBOTIC DEBURRING OPERATIONS

Carlos M. O. Valente
Advanced Manufacturing Center (NUMA)
University of São Paulo at São Carlos
Av. Trabalhador Saocarlense, 400, 13566-590, São Carlos, SP
cmov@sc.usp.br

João F. G. Oliveira
Advanced Manufacturing Center (NUMA)
University of São Paulo at São Carlos
Av. Trabalhador Saocarlense, 400, 13566-590, São Carlos, SP
jfgo@sc.usp.br

Abstract. *Robotic deburring has been used by industries to automate the manual operation, which is a constant source of problems related to lack of productivity and high risk of accidents. However, the automation of the deburring operation is not a trivial task. The high interaction between the tool and the workpiece, associated with the inconsistency of the burr formation, represents a big challenge to the programming and controlling system applied to the robots. This paper proposes a complete framework for an efficient robotic deburring implementation. The framework aims to integrate all the steps of the robotic implementation: trajectory programming for efficient burr removal, contact evaluation and definition of the control parameters, and finally the online trajectory control. The proposed controller combines two signals into a new parameter, Fast Abrasive Power (FAP), which represents a modularization of the power level by the ratio between instantaneous acoustic emission (AE) and average AE calculated over the last n points. The new fast power parameter maintains the reliability of the original power signal and incorporates the dynamics of the AE signal.*

Keywords*. robotic, deburring, grinding, path control, off-line programming.*

1. Introduction

Burr is defined as an undesirable projection of material formed as the result of plastic flow from a cutting or shearing operation (Ko and Dornfeld, 1991). Although burrs were considered a secondary operation within the machine processes, several aspects have been modifying the way burrs are handled during the machine processes. Deburring processes have been identified as the bottleneck in many machine industries (Balasubramaniam et all, 1998). The burr removal methods can induce dimensioning errors to the workpiece if improperly executed (Dornfeld and Lisiewicz, 1992). Finally, burrs may cause problems in further processes, such as handling and assembling operations.

Despite of the latter advances in the burr minimization techniques (Nakayama and Arai, 1987; Olvera and Barrow, 1996; Chern and Dornfeld, 1996; Nakayanaswami and Dornfeld, 1997; Min, 1999), the development of new materials and the progress of machine techniques require a continuous improvement to the deburring methods (Proctor, 1989). Several automated solution have been proposed in order to substitute the manual deburring. However, despite the fact of being an extremely unsafe and non-ergonomic operation, manual deburring methods are still widely applied by manufacturing industries. The result of the manual operation is highly depended on the operator's skills and it is subject to enormous quality deviation (Sickle and Flores, 1997). The process requires a constant attention of the operator that is subject to noise, pollution, dirty and vibration. These factors turn the deburring operation into a dangerous, difficult, costly, slow, and high subjected to errors, which are very expensive due to the fact that they can damage a workpiece on its final step.

The disadvantages of the manual method lead to the automation of the deburring process. Several automated solutions were proposed, varying from the development of specialized equipments (electro-chemical deburring, thermal-energy deburring, vibratory deburring, centrifugal deburring, ultrasonic deburring, abrasive jet deburring, etc), the implementation of a final deburring pass in the same CNC machine where the burr was formed, and finally the use to industrial robots. Each alternative has its particularities and is more suitable for some aspects related to the geometry of the workpiece, to its material and to the requirement for edge finishing (Gillespie, 1996).

The most indicated application for robotic deburring operation is the burr removal in workpiece with complex geometry. Due to the motion flexibility of the robots, they can operate all the edges of the workpiece without modifying the clamping position. In addition, they can remove burrs on regions that are impossible for other methods, such as inner sections and intersection of holes. However, in spite of all the advantages listed above, the use of industrial robots for deburring operations is minor. In addition to Jinno et. all (1995), who states that the most exploited robotic applications are material handling and welding, the report presented by the ROBOTIC INDUSTRIAL ASSOCIATION (2001) informs that only 3% of the robots commercialized in the first quarter of 2001 were implemented in material removal operations (chamfering, polishing, deburring). In deburring operations, the high interaction between the workpiece and the robot, associated with the inconsistency of the operations (it is impossible to precisely predict the size and location of the burr) represents a big challenge to the programming and controlling system applied to robotic deburring operations.

The majority of the commercial solutions offered nowadays try to solve the problem described above by increasing the compliance of the system, through the incorporation of passive elements (spring) between the tool and the robot wrist (Warnecke and Abele, 1983). The additional compliance gives the system the ability to adapt to imperfection on the surface, although it doesn't allow an efficient control of the contact between the tool and the workpiece. The lack of control can result in a misaligned and irregular surface. These systems also require a high experience of the operator, because the generated path may become instable if the system is applied to workpieces that present big burrs. In this case, a correct feed rate should be set.

Thus, a more suitable solution for the robotic deburring operation will require a better control of the process. In consequence, the final solution for the robotic deburring points to a more efficient monitoring system, which transfers to the controlling system more information about the material removal process (Craig, 1986). In such context, researchers are looking for a more suitable sensing technique. Several sensors were proposed: force sensors (Her and Kazerooni, 1991; Persons, 1996), infrared visual sensors (Seliger and Hsieh, 1991), acoustic emission sensors (Dornfeld and Erickson, 1989), power sensors, and others. However, each alternative presents its positive and negative aspects (Valente and Oliveira, 2001). Thus, due to the drawbacks and limitations faced by each sensing technique working alone, a control strategy based on sensor fusion is consider as the final solution to robotic deburring applications.

This work aims to develop a complete framework for robotic deburring, consisting on three integrated modules: off-line programming module, contact evaluation module (pre-controlling module) and path control module. Based on the FAP parameter, a real time strategy able to correct the tool path and maintain an adequate contact between the robot tool and the part edge is proposed. The paper is organized as follow. In section 2, the framework for robotic deburring is introduced. In the following sections, each module of the framework is presented in details. Thus, section 3 presents the off-line programming system). Section 4 presents the contact evaluation module. And finally, section 5 presents the path control algorithm.

2. Framework for robotic deburring

In this paper, a complete framework for an efficient robotic deburring implementation is proposed. The framework includes all the steps for process programming and controlling, and it is composed by three integrated modules, according to Fig. (1).

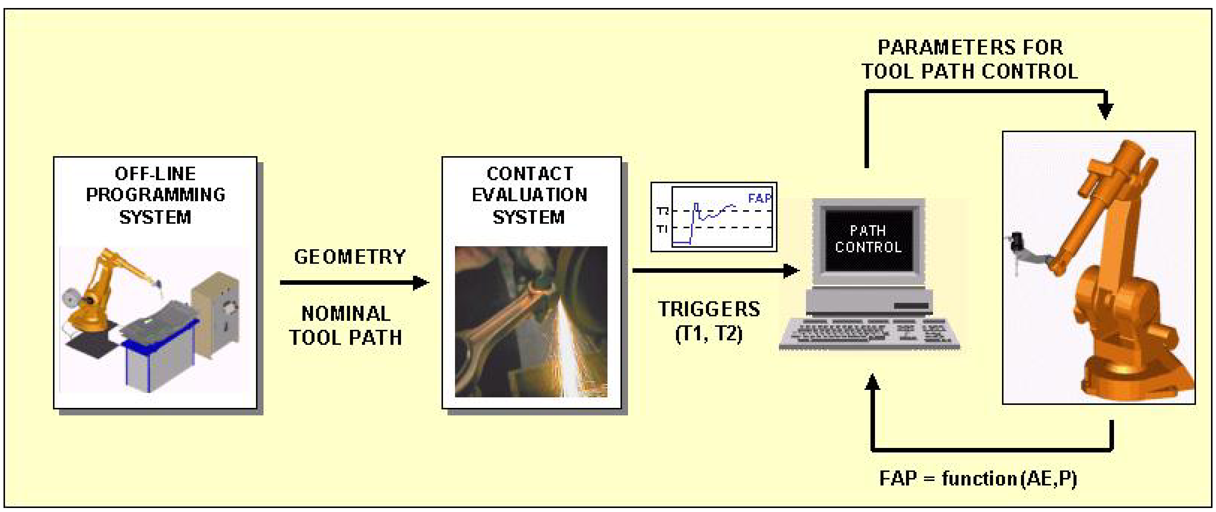


Figure 1. Complete framework for robotic deburring, based on three integrated modules: off-line programming system, contact evaluation system and tool path control.

The first step consists of a tool path programming, implemented on a graphical software. In this phase, the entire deburring environment (workpiece, clamping system, constraints, etc) can be drawn or imported from any CAD software. Using this scenario, the tool path is graphically defined in order to machine the edges where burrs are expected. The output of this system is the tool path program, formed by a sequence of commands that defines the nominal trajectory of the tool.

The next module is called the Contact Evaluation Module. This module reads the deburring program (generated by the first step) and analyzes each segment of the trajectory. In summary, the second module extracts the linear and circular segments that compose the global path, and calculates the controlling parameters for each segments based on an evaluation of the contact between the tool and the workpiece. The output is a list of triggers (controlling parameters), where each set of triggers is associated to one segment of the trajectory.

Finally, an active tool path control is proposed, using the nominal path defined by module 1 and the controlling parameters adjusted by module 2. Thus, the system follows the nominal path and executes corrections on such path when the adequate interaction between the tool and the workpiece is being affected by the presence of burrs or any other imperfection of the surface (misalignment, etc). The path control is designed over an innovative strategy that is based on the combination of two signals: power and acoustic emission.

In the following sections, each module will be described in details.

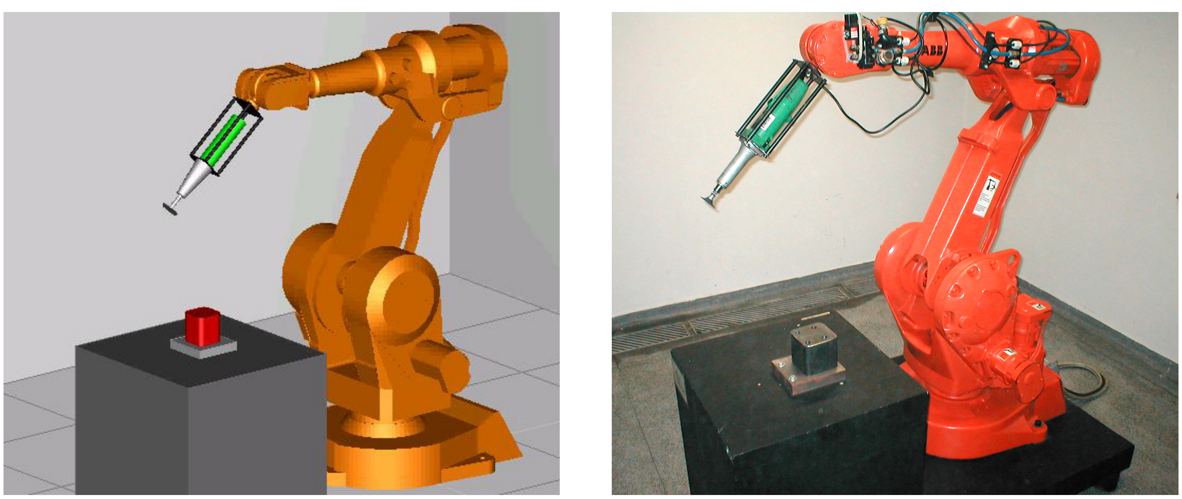
3. Deburring path programming

More complex robotic tasks and the continuous requirement for reduction of process time are some of the aspects that result in more complex programs for robotic applications. According to Brown (1998), the definition of the tool path in the case of complex workpieces (i.e. castings and engine blocks) may demand more than 1500 sequential movements. Hence, it may take at least three days for an experienced operator to generate (using teach-in method) the entire sequence of command of the deburring program, if the new program is based on parts of existing programs. Nevertheless, for a complete new workpiece, the programming task can last up to one month. In such situation, the application of off-line programming technique may offer many advantages.

According to Roos and Behrens (1997), off-line programming is a technique characterized by the generation of the program (sequence of commands) freed from the robot control or a programming device, which allow its execution in advance or in parallel to the robotic application. Persoons (1997) identifies three types of off-line techniques and indicated the graphical simulators as the most used. These softwares are based on CAD technologies, and combine graphical facilities with algorithms to model the kinematical and dynamical behavior of the robots. The main advantages of the off-line programming are the dramatic reduction of the programming time and the possibility of simulating the program before its use. The main consequences are the optimization of the cycles, reduction of the production time, pre-checking of movements, reduction of programming errors and improvements in safety. So, according to Weck and Dammertz (1995), the off-line programming can be consider as one of the most important factor that leads to an economical implementation of industrial robots in deburring of small or medium batch.

However, this technique also presents some limitations. Once the CAD systems are based on ideal mathematical models, which assume that the robots have perfectly stiffen joints and no backlash. The problem lays exactly in the intrinsic imperfection of the real mechanisms: deflection of the joints, wear and backlash of the mechanisms, offset of the encoders/resolvers, and influences of the environment (vibration and temperature). These imperfections can be minimized, but can never be completely eliminated. In summary, the imperfections compromise the accuracy of the robots and modify the ideal scenario created in the simulators. Thus, Brown (1998) states that fine adjustments on the program, mainly changes on the coordinates of programmed points, must necessary be executed online (using the robot) in order to adjust the model to the real behavior of the robot. However, even considering this extra adjustment time, the off-line programming technique still results in a dramatic reduction of the programming time.

Figure (2) presents the robotic modeling created for the deburring application. It also presents the real scenario, which confirms the efficiency of the graphical simulation. The simulation was developed using the software Workspace 5 ™, from Flow Software Technologies. The robot model (ABB IRB 2400/10) was imported from the software library, and the other components of the scene were created: end-effector (deburring tool attached to the wrist of the robot), workpiece and the complete fixture system.



(a) (b)

Figure 2. Comparison between the simulated model (a) and the real scenario (b) for robotic deburring.

The TCP (tool center point) was defined on the surface of the abrasive disk, which is mounted at the tip of the deburring tool. This point defines the best position of the disk that will make contact with the workpiece. On the surface of the workpiece, several points called geometric points (GP) are also created. The sequence of points defines the tool movement, which links the GPs by lines and curves. Some shots of the movement made by the tool during the deburring simulation are illustrated in Fig. (3).

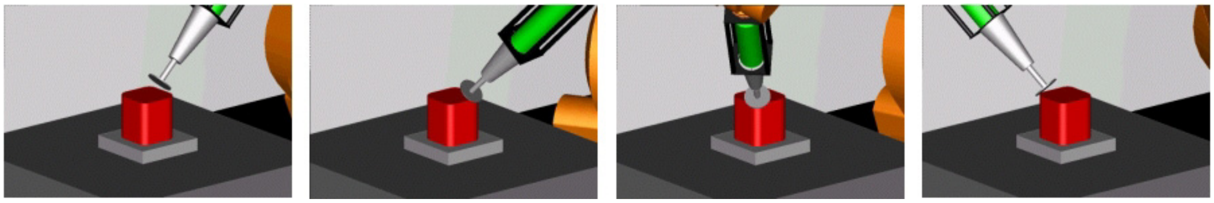


Figure 3. Sequence of movements executed during the robotic deburring simulation.

The deburring movements can be converted to a sequence of commands that are interpreted by the robot, according to the language syntax created by the robot's manufacturer, called RAPID. In such syntax, some of the motion commands are: linear movement (MOVEL), circular movement (MOVEC) and free movement with no required trajectory (MOVEJ). The program associated to the sequence movements presented in Fig. (3) is described in Table (1):

Table 1. Program generated by the software as a result of the deburring simulation.

Commands	Description
MoveJ Aprox,v500,z1,t_Deburring_Tool;	*Approaching movement*
MoveL Contact,v200,fine,t_Deburring_Tool;	*Movement forward the "Contact" point located on the surface of the workpiece (Fig. 3a)*
MoveL P11*,v100,fine,t_Deburring_Tool;	*Deburring action on half of edge 1*
MoveC P1C*,P12,v100,fine,t_Deburring_Tool;	*Deburring action on vertex 1*
MoveL P21*,v100,fine,t_Deburring_Tool;	*Deburring action on edge 2 (Fig. 3b)*
MoveC P2C*,P22,v100,fine,t_Deburring_Tool;	*Deburring action on vertex 2 (Fig. 3c)*
MoveL P31*,v100,fine,t_Deburring_Tool;	*Deburring action on edge 3*
MoveC P3C*,P32,v100,fine,t_Deburring_Tool;	*Deburring action on vertex 3 (Fig. 3d)*
MoveL P41*,v100,fine,t_Deburring_Tool;	*Deburring action on edge 4*
MoveC P4C*,P42,v100,fine,t_Deburring_Tool;	*Deburring action on vertex 4*
MoveL Final*,v100,fine,t_Deburring_Tool;	*Deburring action on the other half of edge 1*
MoveL Final2,v500,z1,t_Deburring_Tool;	*Backward movement*
MoveJ Home,v500,fine,t_Deburring_Tool;	*Return to home position*

*Geometric points (GPs) located at the edges of the workpiece. The sequence of GPs defines the deburring path.

The next step of this research is the integration of the robotic simulation with the graphical system for burr prediction, which has been developed by the Laboratory for Manufacturing Automation of the University of California at Berkeley (Rangarajan, 2001; Bansal and Lee, 2002).

4. Contact evaluation module

The next module proposed in the robotic deburring framework evaluates the contact between the tool and the workpiece during the execution of the nominal path. This path is defined by a sequence of movements formed by linear and circular segments. The combination of different segments is used to interpolate the geometry of the outline of the workpiece. Hence, when executing the programmed movements, the tool will follow the edges of the workpiece and consequently will remove burrs that may be located there.

Nonetheless, the interaction between the tool and the workpiece changes depending on the geometry of the segments. Figure (4) illustrates the effective contact area in two different situations: a linear segment and a circular segment.

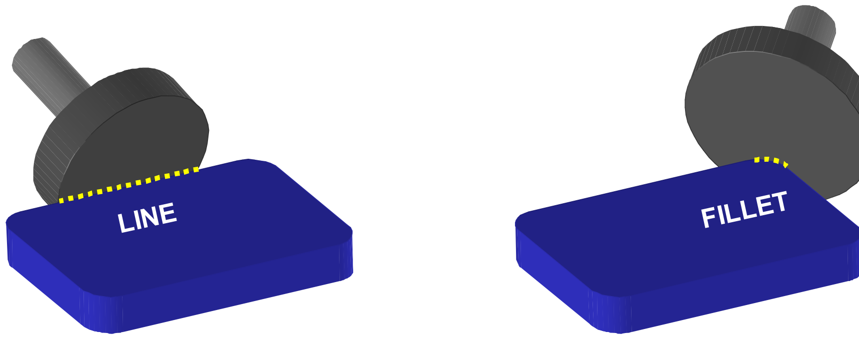


Figure 4. Illustration of the effective contact area for a linear segment and a circular segment (fillet).

Analyzing the effective contact geometry in combination with the power model for grinding proposed by Malkin (1989), it is possible to understand the influence of the deburring trajectory in the amount of power consumed by the operation. According to Malkin's formulation, the grinding power is composed by three components:

$$P = P_{CH} + P_{PL} + P_{SL} \quad (1)$$

where,

P_{CH} = power component due to the chip formation;
P_{PL} = power component due to plowing;
P_{SL} = power component due to sliding.

The power due the chip formation is a function of the material removal rate (MMR), while the power due to plowing depends on the tangential velocity of the grinding wheel and the width of the contact. Finally, the sliding portion is dependent on the friction coefficient and the real contact area (wear flat areas), which is highly influenced by the geometry of the contact and the dressing condition of the grinding wheel.

As a result, considering the same chamfer size of and the same tool feed rate during the complete deburring trajectory, the MMR will be constant and so will be the power component due to chip formation. Thus, the P_{CH} component depends only on the process parameters (chamfer size or depth of cut and feed rate) and it is not influenced by the geometry of the edge.

However, the other two components, power due to plowing and sliding, are highly dependent on the geometry of the contact. Therefore, a larger contact area will require a higher value of sliding and plowing power, which will increase the total amount of power consumed by the operation. By this assumption, it is possible to conclude that, during the deburring trajectory, a higher amount of power will be required for linear segments because of a large area of contact. In contrast, at fillets and other circular segments, the power consumption will be smaller.

The contact module proposed in this paper uses the program generated by the previous module (off-line programming module) as an input, according to Fig. (5). Each motion instruction of the program is analyzed in separate and the geometry associated to the movement is extracted. In the figure, an illustrative workpiece was used to demonstrate the algorithm. The portion of the surface highlighted in the figure is formed by a circular segment with radius of 30 millimeters, a linear segment and another circular segment with radius of 15 millimeters. In the programming module, each segment is processed and the motion instructions are generated. After that, the contact evaluation module reads each instruction related to a deburring action and re-designs the geometry of the segment. In this case, the geometries are two fillets with different radius separated by a line. Each geometry is inputted into a modified version of the Malkin's model for grinding, together with the other parameters used in the process (desired chamfer size, the tool feed rate and the wheel speed). The result is the appropriate power level that should be kept constant during the deburring operation at the segment in analysis. Note that a higher power level is calculated for the linear segment. Comparing the circular segments, the one with a smaller radius (smaller contact area) is associated with a lower power consumption. This algorithm is applied to all the instruction of the program related to deburring, and the result is a list of appropriate power values.

The original model proposed by Malkin considers a parallel grinding (Fig. 6a), in which the contact geometry is constant in the direction longitudinal to the wheel axis. In this case, Hahn and Lindsay (1971) created the concept of equivalent diameter that interrelates the geometric contact of a cylindrical grinding (external or internal) to a planar grinding operation. Using the equivalent diameter definition, the contact length can be calculated independent of the wheel diameter and the workpiece edge geometry by the Eq. (2). In Malkin's model, the contact length simplifies the formula of the contact area (Eq. 3) used to calculate the component of power due to sliding.

$$l_c = \sqrt{a \cdot D_E} \tag{2}$$
$$A = l_c \cdot b \tag{3}$$

where,

l_C= contact length;
a = depth of cut;
b = contact width;
D_E = equivalent diameter.

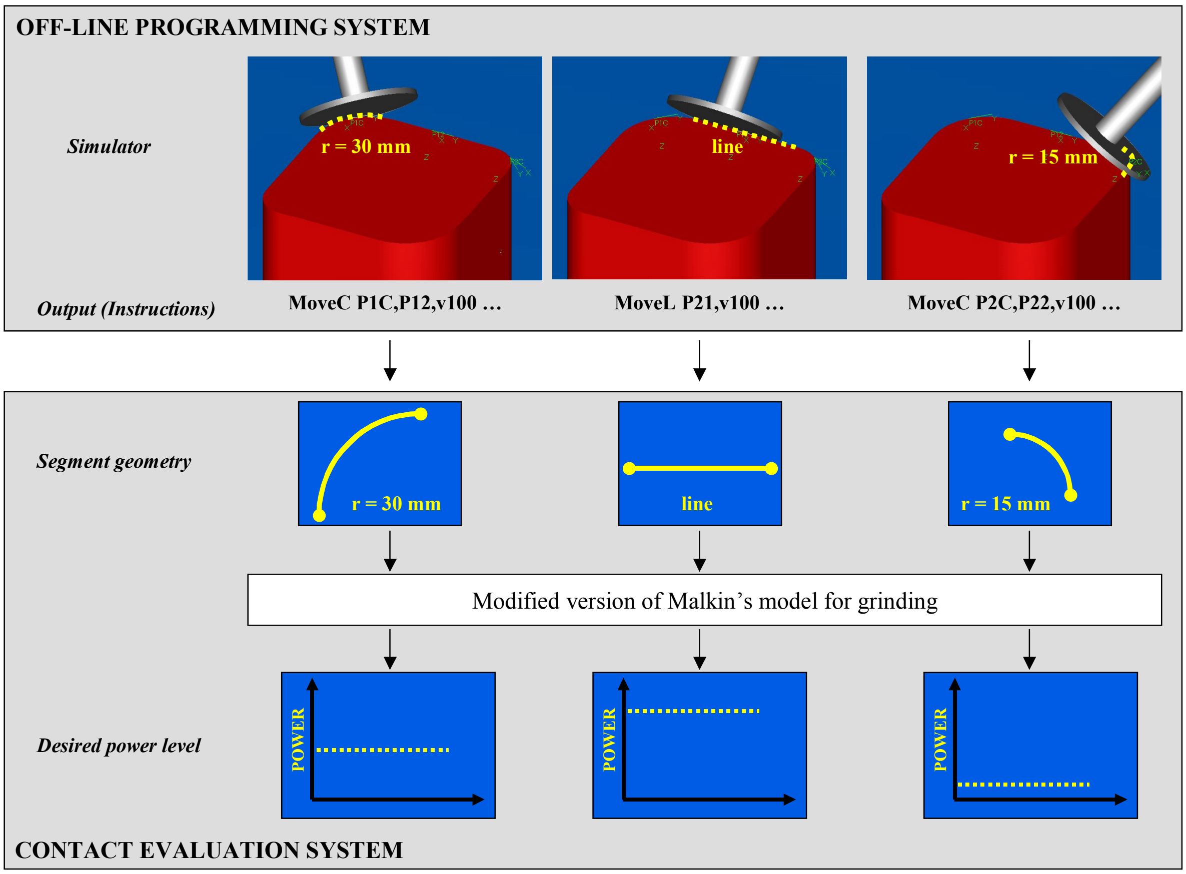


Figure 5. Algorithm used in the contact evaluation system to calculate the desired power level for each trajectory segment.

However, in the deburring/chamfering case, the Hahn's equation for the equivalent diameter is not valid due to a completely different contact geometry (Fig. 6b). Therefore, this paper proposes a modified formulation for Malkin's model, which includes new equations to calculate the contact length and the contact area. This work is under development. In the first step, several chamfering experiments were conducted in order to establish a relation between power level and chamfer size for different tool feed rate values. In all the experiments, linear chamfering trajectories (180 millimeters long) were executed over sharp edges of steel plates (SAE 1020). Using the concept of equivalent diameter, the results of these experiments can be extrapolated to any circular trajectory. More details these experiments are presented by Valente and Oliveira (2002). In parallel, the modified version of Malkin's model has been formulated. In this new version, new formulae for the material removal rate and the contact area have been proposed. The next step is the adjustment of the parameters of the new formulation and the validation of the new model for all the chamfering experiments described above.

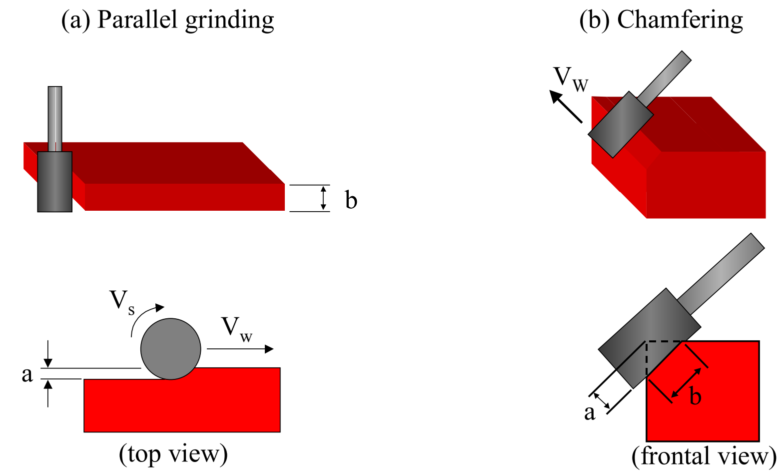


Figure 6. Difference of the contact geometry in grinding operations due the variation of the grinding wheel orientation: (a) parallel grinding; (b) chamfering operation.

5. Active Path Control

The final step proposed by the robotic framework represents an innovative method able to monitor and control the robot path during the automated deburring operation. This system is based on the nominal trajectory generated by the off-line programming module and the list of required power level associated with every segment of the trajectory. The module aims to control the effective path of the deburring tool in order to maintain the power signal as close as possible to its target level. Online correction of the programming path can be order by the control module if edge imperfections are detected. These imperfections are identified by modifications of the power level.

The control strategy is based on two signals, which are the most used data for monitoring abrasives processes: acoustic emission and power. The AE information presents an extremely fast and consistent local response and is very suitable to detect surfaces contacts. But the AE level does not present a uniform behavior during the hole process and can be influenced by other parameters (part geometry, sensor position, etc.) which does not depends on the contact interaction between the tool and the part edge. In contrast, the power level is proportional to the amount of material removed from the workpiece, but it is characterized by a damped response due the motor inertia. Therefore, to improve the performance of an AE and power feedback system, it is proposed a sensor fusion through the following equation:

$$FAP = K \cdot \frac{EA}{\overline{EA}_n} \cdot \left(P - P_o\right) \tag{4}$$

where,

FAP = Fast Abrasive Power;
K = signal gain;
P = instantaneous power;
P_0 = power (no motor load);
EA = instantaneous AE;
EA_n = average AE calculated over the last n points.

The FAP parameter represents a modularization of the original power signal by the ratio between the instantaneous AE and the average AE over the last n points. This ratio considers only the local response of the AE and filters its inconsistent behavior during the process. Furthermore, the influence of the AE signal on the FAP parameter can be adjust by the size *n* of the average window. Hence, the new FAP parameter incorporates the AE dynamics to the reliability of the power signal. More information about the FAP parameter and its behavior during the chamfering process can be found in Valente and Oliveira (2001).

The control strategy, based on the FAP parameter, is illustrated in Fig. (7). This strategy was implemented in LabView 5.1 from National Instruments, running on an external PC. According to the figure, the FAP level is compared with two limits that define the working range for the FAP parameter. Thus, a value of FAP higher than T2 indicates a high-intensive contact and controlling signals are sent to the digital I/O interface of the robot. In contrast, when the FAP level is lower than T1, the robot receives control parameters that indicate a lack of contact. Using this electrical configuration, the following algorithm is implemented for robot path correction:

- If the FAP level is lower than T1, the deburring tool is loosing contact with the workpiece and it should be moved toward the edge until the FAP value returns to the working range.
- If the FAP level is higher than T2, the contact has exceeded the appropriate limits, what can damage the tool and/or the workpiece. Thus, the tool should be moved backwards until the FAP value returns to the working range.
- The tool should follow its programmed path when the FAP level lays in the working range, which indicates an adequate contact.

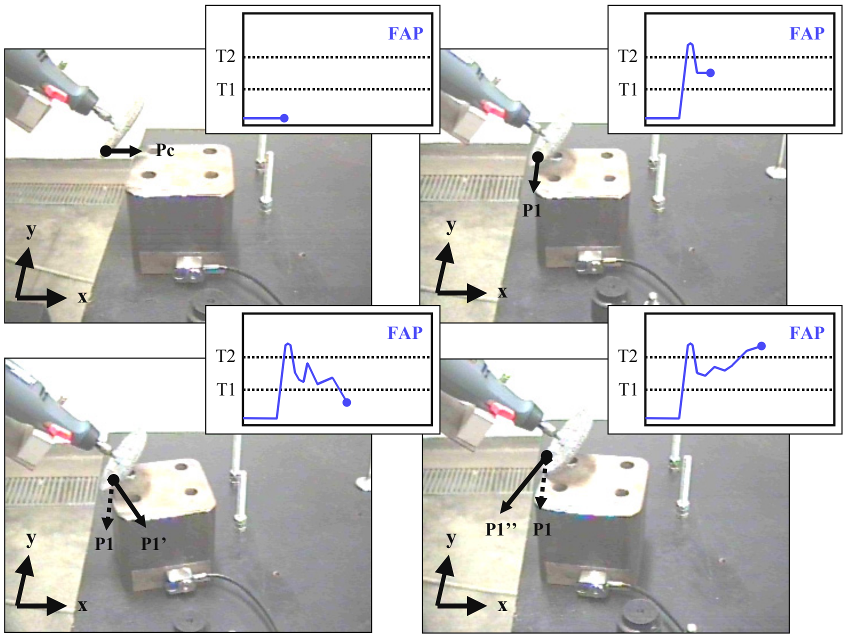
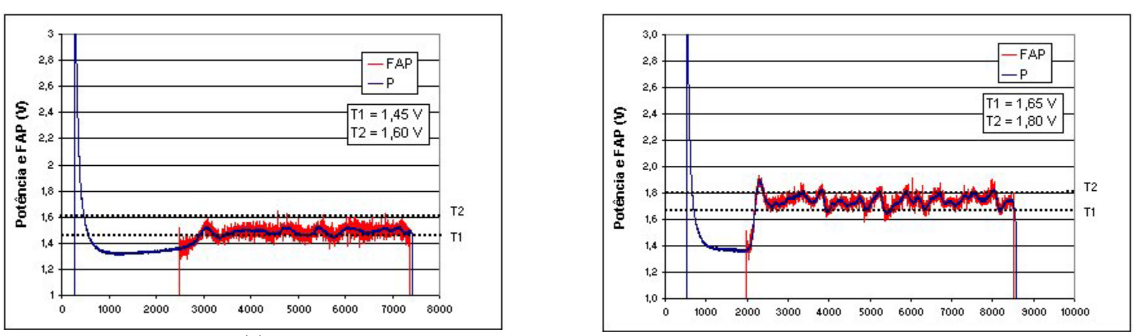


Figure 7. Strategy for tool path control, based on the FAP parameter. The objective of the controller is to maintain the FAP level within the working range (defined by the limits T1 and T2): (a) automatic detection of contact point P_c; (b) move towards point P1 while FAP is within the working range; (c) move the target point to a new position (P1') in order to avoid lack of contact; (d) move the target point to a new position (P1'') in order to avoid an intense contact.

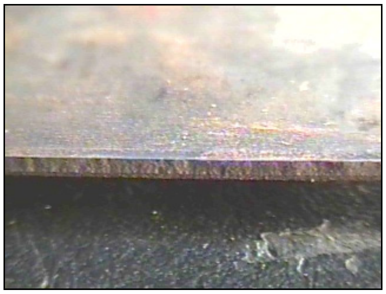
The results of the path control system are presented in Figs. (8) and (9). Two different tests were performed. In both tests, the FAP parameter was calculated using $n = 3$ points. In the first test, the objective was to machine a chamfer of 0.5 mm. Considering the tool feed rate f = 5 mm/sec, the appropriate limits T1 and T2 can be calculated according to the calibration results presented in Valente and Oliveira (2002). Thus, the following values were adopted: T1 = 1.45 V e T2 = 1.60 V. Note that the algorithm was able to control the FAP level within the working range. It is important to show up that the power level (blue line) oscillated within a narrower band, what confirms the success of the control algorithm. In the second test, the limits were changed aiming to machine a larger chamfer, 0.65 mm. In this case, the limits were T1 = 1.65 V e T2 = 1.80 V. Again, the control strategy succeeded.



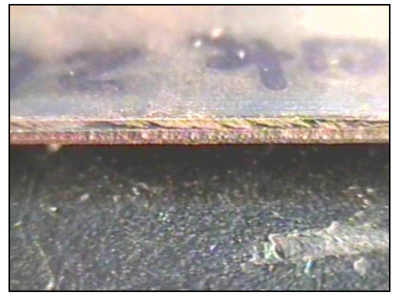
(a) (b)

Figure 8. Results of the path control strategy during the robotic deburring operation, showing power (blue line) and the FAP parameter (red line): (a) working range defined for a desired chamfer of 0,5 mm; (b) working range defined for a desired chamfer of 0,65 mm.

The tests described above can also be analyzed by the photos and measurements of the machined chamfers (Fig. 9). Analyzing the first picture, it is possible to observe a smooth chamfer, which was already expected due to a stable response of the power signal. However, the second chamfer presents a worst surface quality, consequence of a larger variation of the power signal. This quality can be optimized by improvements in the path control strategy. Finally, the measurements of the machined chamfers results in 0.58 mm and 0.72 mm. These dimensions are close to the desired ones, respectively, 0.50 mm and 0.65 mm.



(a)



(b)

Figure 9. Photos of the machined chamfers, resultant of the robotic deburring operation: (a) first test with a desired width value of 0.50 mm; (b) second test with a desired width value of 0.65 mm.

6. Conclusions

This work proposes a complete framework for an efficient robotic deburring implementation. The framework aims to integrate all the steps of the robotic implementation, since the trajectory programming to the trajectory control. As an intermediate step, a new version of Malkin's model is proposed in order to evaluate the contact between the deburring tool and the workpiece.

The main advantage of the off-line programming technique is the big reduction of cycle time. In this framework, it is also proposed an integration of the programming system with the burr prediction system. Thus, the software operator can define a more effective deburring trajectory based on a previous estimation of the size and location of the burr.

Finally, the path control module is based on an innovative strategy that combines two sensor signals: acoustic emission and power consumed by the deburring head motor. The fusion of these signals results in a new control parameter, Fast Abrasive Power (FAP), which maintains the reliability of the power signal and incorporates the dynamics of the acoustic emission. Analyzing the results, it is possible to establish a relationship between the FAP parameter and the amount of material removed from the workpiece, as well as use this relationship to control the contact within an adequate range.

7. Acknowledgements

This work is supported by FAPESP (Fundação para Amparo à Pesquisa do Estado de São Paulo). We also would like to acknowledge the collaboration of the Recope de Automação regarding the software Workspace 5.

8. References

Balasubramaniam, R., Krishnan, J., Ramakrishnan, N., 1998, "Investigation of AJM for deburring", Journal of Materials Processing Technology, Vol. 79, pp. 52-58.

Bansal, A., Lee, K., 2002, Tool Path Planning in Conjunction with Exit Order Sequence, LMA Report, University of California, Berkeley.

Brown, L., 1998, "The development of software to assist in off-line programming for robotic fettling of cast components", Industrial Robot, Vol. 25, No. 4, pp. 282-287.

Chern, G.; Dornfeld, D.A., 1996, "Burr/breakout model development and experimental verification", Journal of Engineering Materials and Technology, Vol.118, pp.201-206.

Craig, J.J., 1986, "Introduction to robotics, mechanics and control", Ed. J.Wiley, New York.

Dornfeld, D.A., Erickson, E., 1989, "Robotic Deburring with real time acoustic emission feedback control", PED ASME, Vol. 38, pp. 13-25.

Dornfeld, D.A., Lisiewicz, V., 1992, "Acoustic emission feedback for precision deburring", Annals of the CIRP, Vol. 41, No. 1, pp. 93-96.

Gillespie, L. R., 1996, "The Battle of the burr: new strategies and new tricks", Manufacturing Engineering. Vol.116, No.2, pp.69-78.

Hahn, R.S, Lindsay, R.P., 1971, "Basic relationship in precision grinding", In: Principles of grinding, Machinery, July, pp.55-62.

Her, M.G., Kazerooni, H., 1991, “Automated robotic deburring of parts using compliance control”, Journal of Dynamic Systems, Measurement and Control, Vol. 113, pp. 60-66.

Jinno, M., 1995, “Development of a force controlled robot for grinding, chamfering and polishing”, Proceedings of the IEEE International Conference on Robotics And Automation, Nagoia, Japan, pp. 1455-1460.

Min, S., 1999, Mesh Separation Criteria in Finite Element Simulation for Drilling Burr Formation, LMA Report, University of California, Berkeley.

Ko, S.L.; Dornfeld, D.A., 1991, “A study on burr formation mechanism”, Journal of Engineering materials and technology, Vol.111, pp.75-87.

Malkin, S., 1989, “Grinding technology. Theory and applications of machining with abrasives”, Ellis Horwood Limited, England.

Nakayama, K.; Arai, M., 1987, “Burr formation in metal cutting”, Annals of the CIRP, Vol.36, No.1, pp.33-36.

Narayanaswami, R.; Dornfeld, D.A., 1997, “Burr minimization in face milling; a geometrical approach”, Journal of Manufacturing Science and Engineering, Vol.119, pp.170-177.

Olvera, O.; Barrow, G., 1996, “An experimental study of burr formation in square shoulder face milling”, International Journal of Machining Tools and Manufacturing, Vol.36, No.9, pp.1005-1020.

Persoons, W., 1997, Model based off-line programming of robots, Katholieke Universiteit Leuven, Leuven, Belgium.

Proctor, F. M.; Murphy, K. N., 1989, “Advanced deburring system technology”, Proceeding of the Winter Annual Meeting of the American Society of Manufacturing Engineers, San Francisco, CA, USA.

Rangarajan, A., 2001, Tool path planning based on feature priorities. LMA Report, University of California, Berkeley.

Roos, E., Behrens, A., 1997, “Off-line programming of industrial robots – Adaptation of simulated user programs to the real environment”, Computers in Industry, Vol.33, pp.139-150.

Seliger, G., Hsieh, H.L., 1991, “Sensor-aided programming and movement adaptation for robot-guided deburring of castings”, Annals of the CIRP, Vol. 40, No. 1, pp. 487-490.

Sickle, C. V., Flores, G., 1997, “How to pick the right deburring process”, Manufacturing Engineering, pp .56-62.

Valente, C.M.O., Oliveira, J.F.G., 2001, “Power and acoustic emission feedback for the robotic deburring control”, Proceedings of the 16th Brazilian Congress of Mechanical Engineering, Uberlândia, Brazil.

Valente, C.M.O., Oliveira, J.F.G., 2002, “Several strategies for monitoring robotic deburring system”, Proceedings of the II National Congress of Mechanical Engineering, João Pessoa, Brazil.

Warnecke, H.J., Abele, E., 1983, “Fettling of castings with industrial robots”, Annals of the CIRP, Vol. 32, No. 1, pp. 405-409.

Weck, M.; Dammertz, R., 1995, “OPERA, a new approach to robot programming”, Annals of the CIRP, Vol.44, No.1, pp.389-392.