Hybrid Force/Position Control
in Robotic Deburring

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ABSTRACT

The work presented here is the development of a new strategy for precision deburring and grinding. Hybrid force/position control has been proposed as an approach to satisfy the requirement of this new strategy. The "sensitivity" and "bandwidth" of the hybrid force/position control are the design parameters in this approach. Some experiments have been described to verify the theoretical results.

INTRODUCTION

Since deburring and grinding are finishing processes, parts have the most value added at this stage of production. Deburring must be performed economically and must not produce scrap or rework. This is a major reason for the development of an automated deburring and grinding operation. In most cases, burrs must be removed to allow proper fitting of assembled parts and to insure safe and proper functioning. On high-temperature, high-speed rotating parts, deburring is further required to reduce turbulent gas flow, maintain dynamic balance, and relieve localized stress. For these types of parts, the term "precision deburring" is used. The final geometry of a deburred edge must remain within a given set of tolerances. The surface produced on the edge is required to be a high quality finish. According to the above points, the deburring and grinding of machined parts is a major area of concern in improving manufacturing quality. Typically, manual deburring is the only deburring method available, and represents a time-consuming and expensive solution. Deburring costs for some cast parts can be as high as 35% of the total part cost. References (1,4,6,19,20,22,23 and 25) contain valuable contributions from previous research.

Although robotic deburring is a task with final geometric specifications, the contact forces in the normal and tangential directions are a fundamental part of the process. Robotic deburring and grinding has mostly been studied as a trajectory following task. The necessity of control on the normal and tangential forces, in addition to geometrical surface finish specifications, brings the concept of hybrid force/position control into our consideration. It seems logical that in some instances one develops electronic compliancy (hybrid force/position control (18,24) or impedance control (7-10)) on an active end effector rather than on the entire robot manipulator (15-17).

GEOMETRIC AND QUALITATIVE MODEL OF THE BURR

In this section is described several quantitative and geometric properties of burrs formed in the cutting process. These properties, which are independent of the control algorithm lead us to development of a simple dynamic model for the cutting process. The control algorithm used in the deburring project is benefited by this dynamic model.

Burrs are formed by many manufacturing
processes and the type of burr formed depends directly on the process used and the prevailing conditions. The size and orientation of the burrs on a part is completely random in nature. A dimensional model of a burr work piece edge was generated from statistical data of burr height and root thickness measurements on aircraft engine parts.

Using this data, an average burr can be modelled with a height of 0.25mm to 0.75 mm (0.010" to 0.030"), and a thickness of 0.025mm to 0.075 mm (0.001" to 0.003"). For the overall data, however, the burr heights ranged from zero (a sharp corner) to 1.5 mm (0.060"), and the root thickness from zero to 0.23 mm (0.009"). A typical burr for any particular part therefore, is highly variable.

The burr removal tools chosen for this research were rotary files which produce a 45 degree chamfer on the workpiece edge if the tool is held orthogonal to the part surface. To insure the complete removal of a given burr, the chamfer width must be larger than the root width, as seen in Figure 1.

![Figure 1: Typical Profile of a Burr on a Part Edge](image)

The material removal rate (MRR) of a deburring pass is a function of the velocity of the tool bit along the edge and the cross sectional areas of both the chamfer and the burr. This relationship can be expressed as:

\[
MRR = \frac{A_{\text{chamfer}} + A_{\text{burr}}}{V_{\text{tool}}} \quad (1)
\]

\[
MRR = A_{\text{chamfer}} \left( R_{\tan}^{-1} + 1 \right) V_{\text{tool}} \quad (2)
\]

where: \( R_{\tan} = \frac{A_{\text{burr}}}{A_{\text{chamfer}}} \)

Note that equations 1 and 2 are geometric relationships. Even though each parameter in equations 1 and 2 can be a function of other parameters, such as contact forces and the stiffness of the material, the MRR can always be specified with a given set of geometric variables: feedrate, depth of cut and burr area. These variables are a function of other variables depending on the control strategy used in the deburring process. The above intuitive equations do not reveal the dynamic behavior; they only emphasize the proportionality of MRR with feed rate, depth of cut and chamfer area. \( R_{\tan} \) can vary in process from zero for sharp corners, to 0.2 for average burrs, to the worst case ratio of 2.0 depending on the chosen \( A_{\text{chamfer}} \). Therefore MRR for a given velocity and a desired constant chamfer can vary up to 200% depending on the size of the burr.

In the deburring process, the cutting force in the tangential direction is proportional to MRR [5]. The tangential area ratio, discussed previously, indicates that the worst case variations in burr size produce significant variations in the tangential force. If the burr and chamfer areas are projected in the normal direction perpendicular to the edge, the area ratio varies from zero for a sharp edge, to only 0.02 for an average burr, to the worst case value of 0.26.

As such, variations in the burr size should not greatly affect the normal force for a given chamfer. Figure 2 shows the tangential and normal cutting forces for two depths of cut. The grinder proceeds along the edge of a part with constant velocity. The cutting force in tangential direction increases from 2nt to 5nt when the depth of cut is changed form .030"(0.75mm) to .048"(1.2mm) The ratio of the tangential projection for these cases is \( (0.048/0.03)^2 = 2.56 \). This ratio is almost equal with the ratio of the tangential cutting forces \( (5/2 = 2.5) \). The normal force remains relatively constant.

To summarize the results:

1) For a given constant feedrate the tangential force varies very significantly with variation of the burr size; thus every time that the rotary file encounters a large burr, the tangent force increases dramatically.

2) For a given constant feedrate, the normal force stays relatively constant regardless of burr size variation.

Figure 3 shows the proportionality of the tangential cutting force with MRR when an edge similar to one in Figure 1, but without burr, is cut. For a given depth of cut (0.055") of an edge without a burr, the
of 1cm/sec. Note that the relationship between the cutting force and the speed along the edge represents the dynamic behavior of the process. If the speed of the tool along the edge of the part is kept constant, we expect an increase in the tangential force when the cutting tool encounters a burr along the edge of the part.

Figure 3: The tangential force is proportional to the material removal rate

CONTROL STRATEGY (HYBRID FORCE/POSITION CONTROL)

Suppose the cutting tool is being moved by an industrial robot, then the contact force will vary significantly because of the variation of the burr size if the robot is moving with constant speed along the edge. This contact force can be resolved into two orthogonal directions as in Figure 4. If the contact force is large due to the size of the burr, a separation of the robot from the part will occur. We desire to develop a self-tuning strategy such that the contact force in the cutting process is minimized. A small contact force guarantees that the endpoint of the robot stays very close to the part without separation. Consider the deburring of a surface by a robot manipulator; the objective is to use an end-effector to smooth the surface down to the commanded trajectory depicted by the dashed line in Figure 4. It is intuitive to design a trajectory control mechanism for the manipulator with a small sensitivity in the normal direction and a force control in the tangential direction.

The trajectory control in the normal direction causes the endpoint of the grinder to reject the interaction forces and stay very close to the commanded trajectory (dashed-line). We define the
sensitivity as the ratio of the robot motion to the interaction force. One can describe the disturbance rejection property of a trajectory control system by a sensitivity function. A small sensitivity results in a stiff system. The smaller the sensitivity of the trajectory control in the normal direction, the smoother the surface will be. Given the volume of the metal to be removed, the desired tolerance in the normal direction prescribes an approximate value for the sensitivity of the trajectory control in the normal direction. In practice, one can develop large loop gains (by employment of several integrators) to gain small sensitivity in the system. One natural way of developing small sensitivity in the system, is the employment of the robot in such a configuration that the robot has the highest effective inertia in the normal direction. The high inertia in the normal direction causes the robot to stay very “rigid” in response to interaction forces.

As described previously, the force necessary to cut in the tangential direction at a constant traverse speed is approximately proportional to the volume of the metal to be removed. Therefore, the larger the burrs on the surface, the slower the manipulator must move in the tangential direction to maintain a relatively constant tangential force. This is necessary because the slower speed of the end-point along the surface implies a smaller volume of metal to be removed per unit of time, and consequently, less force in the tangential direction. To remove the metal from the surface, the grinder should slow down in response to contact forces with large burrs. The above explanation demonstrates that it is necessary for the end-effector to accommodate the interaction forces along the tangential direction, which directly implies a force control system in the tangential direction. If a designer does not accommodate the interaction forces by developing a force control system in the tangential direction, the large burrs on the surface will produce large contact forces in the tangential direction (equation 1). It is desired to develop a force control system in the tangential direction so that by varying the velocity of the tool along the edge of the part, a relatively constant force is maintained in the tangential direction. Two problems are associated with large contact forces in the tangential directions:

1) the cutting tool may stall (if it does not break),
2) a slight deflection may develop in the end-point position in the normal direction, which might exceed the desired tolerance. This is due to slight coupling of the force between the normal and tangential directions.

The frequency spectrum of the roughness of the surface and the desired translational speed of the robot along the surface determine the frequency range of operation, \( \omega_b, \) \( \omega_b \) is the frequency range of the burr seen from the end-effector. The bandwidth of the control system in the tangential direction must be larger than \( \omega_b. \) In other words one must travel with such average speed along the edge of the part that \( \omega_b \) falls below the bandwidth of the control system. It is clear that the smaller the value for the commanded tangential force is, the slower the robot will move along the edge of the part. In fact if the commanded force in the tangential direction is very small, the tool will not travel along the edge. This is true, because the controller will drive the system with a small speed to reach to a small force. If a large value is commanded for the force in the tangential direction, then the tool will travel with a large contact force in the tangential direction.

Figure 5 illustrates the architecture of the closed-loop control system for the robot. The detailed description of each operator in Figure 5 is given in references 13 and 16. In the general approach for development of compliance \( E, G, H \) and \( S \) are nonlinear operators.

\( G \) is the square \( n \times n \) transfer function matrix (or a mapping in the nonlinear case) that represents the dynamic behavior of the robot with a velocity controller. The input to \( G \) is an \( n \times 1 \) vector of input velocity, \( \dot{v} \) is the \( n \times 1 \) vector velocity while \( v_0 \) represents the part velocity. \( v_0 \) is zero for stationary fixtures. Both \( \dot{v} \) and \( v_0 \) are expressed in a
global coordinate frame. The fact that most manipulative systems have some kind of velocity controller is the motivation behind our approach. Many methodologies are available for the development of robust velocity controllers. \( G \) can be calculated experimentally or analytically. Note that \( G \) is approximately equal to the unity for the frequencies within its bandwidth. In other words, we assume that a velocity controller has been designed for the robot such that it closely follows all the trajectories with frequency components within the bandwidth of \( G \). \( \omega_n \) represents the bandwidth of \( G \).

\( S \), the \( n \times n \) sensitivity transfer function matrix, is the input velocity for the robot manipulator. The value of the contact force and the end-point tangential velocity of the robot are given by equations 3 and 4.

\[
f = E[(I + SE + GHE)^{-1}Gv_r] \tag{3}
\]

\[
v = [(I + SE + GHE)^{-1}Gv_r] \tag{4}
\]

The goal is to choose a class of compensators, \( H \), to shape the impedance of the system, \( E[(I + SE + GHE)^{-1}G] \), in equation 3. When the system is not in contact with the part, the actual velocity of the end point is equal to the input trajectory command within the bandwidth of \( G \). As noted earlier, \( G \) is approximately equal to the unity within its bandwidth. When the system is in contact with the environment, then the contact force follows \( v_r \) according to equation 3. The input command vector \( v_r \), is used differently depending on whether the tool piece is in contact with the work piece or travelling through unconstrained space. When the manipulative system and part are in contact, \( v_r \) is a command to shape the contact force. The small value for \( H \) in a particular direction implies a very stiff velocity control system. In the limit, when \( H \) is chosen to be zero in a particular direction, the system behaves as a velocity control in that direction. When \( H \) is chosen to be a large number in a particular direction, the system will be very compliant in that direction and small contact forces will be generated. In the deburring process we plan to modulate \( H \) such that it has a small value in the direction normal to the part and a large value in the direction tangential to the part.

\( v_r \) is a trajectory command when it seeks to move the manipulator in unconstrained space. When the robot is not in contact with the part, the robot end point velocity is equal to \( G(v_r) \) or \( Gv_r \) in the linear case.

There is no hardware or software switch in the control system when the robot travels from unconstrained space to constrained space; in our case, when the grinder encounters the work piece. The feedback loop on the contact force closes naturally when the robot encounters the environment (work piece). When the system is in contact with the environment, then the contact force is a function of \( v_r \) according to equation 3.

This compensator must also guarantee the stability of the system. The complete detailed

Figure 5: The Closed-Loop Control for the End-Effector

(or a mapping in the nonlinear case), represents the relationship between the external force on the end point and the end point velocity. This velocity deviation is due to either structural compliance in the end-effector mechanism or the velocity controller compliance. To obtain good velocity control, \( S \) must be quite "small". The notion of "small" can be regarded in the singular value sense when \( S \) is a transfer function matrix. \( L_p \)-norm \((13,16)\) can be considered to show the size of \( S \) in the nonlinear case. \( S \) shows how good a velocity control is.

\( E \) represents the dynamic behavior of the part. In the linear case, \( E \) has been measured from the slope of the plot in Figure 3 and its value is equal to 69.8 nt/cm/sec. In general, one can consider a nonlinear function to characterize \( E \).

\( H \) is the compensator to be designed. The input to this compensator is the contact force. The compensator output signal is subtracted from the input tangential velocity, \( v_r \), to give the error signal,
stability conditions for the nonlinear and linear cases are given in references 13 and 16. The stability for the linear case can be guaranteed if inequality 5 is satisfied.

\[ \sigma_{\text{max}} \left[ H \right] \leq \frac{\sigma_{\text{max}} \left[ E(SE + I_n)^{-1}G \right]}{\sigma_{\text{max}} \left[ E(SE + I_n)^{-1}G \right]} \quad \text{for all } \omega \in (0,\infty) \] (5)

Inequality 5 is true if the mappings in Figure 5 are linear transfer function matrices. If H is chosen outside of this class, instability and consequent separation may occur. If inequality 5 is not satisfied, no conclusion on the stability of the system can be achieved. \( E(SE + I_n)^{-1}G \) is the forward loop transfer function of the system in Figure 5. According to inequality 5, the "size" of H in all directions must be smaller than the reciprocal of the maximum "size" of the forward loop transfer function, \( E(SE + I_n)^{-1}G \). Inequality 5 guarantees the stability of the system if the maximum singular value of H is chosen to be less than the reciprocal of the maximum singular value of \( E(SE + I_n)^{-1}G \). Inequality 5 reveals some facts about the size of H. The smaller the sensitivity of the robot manipulator is, the smaller H must be chosen. Also from inequality 5, the more rigid the environment is, the smaller H must be chosen. In the "ideal case", no H can be found to allow a perfect velocity controlled system \( \Sigma \approx 0 \) to interact with an infinitely rigid environment \( E \approx \infty \). Inequality 5 shows the large value for S develops more range for stability for the closed-loop system. Stability Condition when \( n=1 \) is quite simplified. In the case of the one degree of freedom system the condition for stability is given by inequality 6.

\[ |HG| < |(S+1/E)| \quad \text{for all } \omega \in (0,\infty) \] (6)

\( |.| \) denotes the magnitude of the complex variable. Since in many cases \( G \approx 1 \) for all \( 0<\omega<\omega_0 \), then H must be chosen such that the following inequality is satisfied.

\[ |H| < |(S+1/E)| \quad \text{for all } \omega \in (0,\omega_0) \] (7)

Equation 7 clearly shows that the more rigid the environment is, the smaller H must be chosen to guarantee stability. In the case of a rigid environment ("large" E) and a "good" velocity controlled system ("small" S), H must be chosen as a very small gain.

To guarantee the stability of the closed-loop system in the nonlinear case, H must be chosen such that:

\[ \| H \|_p < \frac{1}{\| V(e) \|_p} \] (8)

Inequality 8 states that the L_p-norm of H must be less than the reciprocal of the "magnitude" of the mapping in the forward loop in Figure 6 where \( \| . \|_p \) represents the p-norm of a function [13]. \( V(e) \) will be equal to \( [E(SE + I_n)^{-1}G] \) when all the operators in the system are linear transfer function matrices.

EXPERIMENTAL SETUP

An experiment was conducted to verify the feasibility of using "hybrid force/position" in robotic deburring. The principal issue in this experiment is to investigate if hybrid force/position methodology can genuinely and reliably meet the deburring specification. Although we acknowledge the influence of many side variables in the deburring process our concern is to study the practicality of the method in metal removing process without introducing extra factors in the experiment. Therefore we employed a high precision and fast XY table for planar maneuvering. Figure 7 shows the experimental set up.
The workpiece to be deburred is mounted on the XY table for maneuvering while the grinder is held vertically by a stationary platform. The sample part is mounted on the table by a sample holder. Depending on the geometry of the sample part, various sample holders can be made. We admit that in the actual deburring process, it may be better to move the grinder by the robot while the part is on a stationary platform. References 15 and 17 describe an active end-effector that can be held by commercial robot manipulators. The XY table is interfaced to a μ-computer for control. Two force sensors between the part and the XY table platform allow for measurement of interaction forces between the part and the grinder. The control algorithm of Figure 5 was implemented on the XY table via the μ-computer. H is chosen to satisfy inequality 6. Because of the lead screw mechanism in the XY table drive, S, the sensitivity of the XY table is very small. H must be chosen such that \(|GH| < 1/E\). Since \(1/E\) is measured as \(1/69.8\) nt/cm/sec, therefore \(H\) is chosen such that the entire loop transfer function \(GH\) has the magnitude is such that \(|GH| < 1/E\). Figure 8 shows the frequency response of table, \(G\), in the tangential direction. As seen in Figure 8, the input velocity command is equal to the output velocity command for about 35 hertz. H can be chosen as any transfer function as long as \(|GH| < 1/E\).

**Figure 8: Frequency Response of G**

**EXPERIMENTS**

We start with the simplest experiment. The objective of this experiment is to substantiate the size of the cutting forces in a straight edge deburring when hybrid force/position control is employed to control the XY table. The parts to be deburred are rectangular steel 2"×.5"×.25" as shown in figure 9.

The edge of the sample part has been filed to produce step burrs as shown in figure 9. Figure 10 shows the tangential and normal force when no force control is employed in the tangential force. The grinder is driven with constant velocity along the edge of the part. As seen in figure 10, once the grinder encounters the burr, the tangential force increased to 25 nt and the deburring tool stalled. Figure 11 shows the tangential and normal forces when a force control strategy according to Figure 5 is employed in deburring the same size burr (depth of cut = .045\(^\circ\)). H in the direction normal to the part is chosen to be zero. H in the direction tangential to the part is chosen to be a large number while satisfying inequality 5. The commanded tangential force is 5 nt and the average speed is 0.088in/sec. Figure 12 shows the tangential and normal force with
the same commanded force in the tangential direction when a burr with the depth of cut of 0.06" is used. Since the tangential force remains constant at 5 nt, the average speed of the system decreases from 0.088 in/sec to 0.057 in/sec. Since the tangential force is kept constant by the force control system, therefore the MRR is constant also. The ratio of the velocities (0.088/0.057=1.6) is inversely equal to the tangential area ratio (0.06/0.045)^2=1.7

Another set of experiments was carried out to investigate the proportionality of the tangential force with the speed when the depth of cut is kept constant. Figure 13 shows the normal and tangential forces when the commanded value for the force control system is set at 2 nt. The burr depth is 0.06". Figure 14 shows the similar forces when 6 nt is commanded for the force control loop. Note that for the same burr depth, the speed of the tool increases when a larger force is commanded for the force control system in the tangential direction. This is true because the tool must travel with a higher speed over the burr to generate the desired tangential force. The average speed of the tool over the burr for the part in Figure 14 is about three times more than the speed of the tool over the burr in Figure 2. This experiment shows the proportionality of the speed with the tangential force to produce a constant volume rate for the material removed.

CONCLUSION
To remove a burr, it is necessary to develop a control strategy which satisfies both geometrical and force constraints in the normal and tangential directions for the frequency range were burrs are seen by the robot. Hybrid force/position control is chosen to satisfy the design rules for robotic deburring and grinding. This paper examined the development and implementation of hybrid force/position control methodology to precision deburring. Some of the theoretical results have been verified experimentally.
REFERENCES


This research is supported by NSF grant, under contract number NSF/DMC-8604123.