Robotic Deburring of Two-dimensional Parts with Unknown Geometry

H. Kazerooni, University of Minnesota, Minneapolis, Minnesota

Abstract

The work presented here is an approach in robotic deburring of two-dimensional parts with unknown geometry. Two problems have been addressed in this paper: tracking the part contour, and control of the metal removal process. The tracking mechanism is a roller bearing mounted on a force sensor at the robot endpoint. The tracking control employs the force measured by this force sensor to find the normal to the part surface, while the deburring algorithm uses another set of contact forces (cutting forces generated by the cutter) to develop a stable metal removal. A set of experimental results is given to verify the effectiveness of the approach.

Keywords: Robotics, Control, Deburring.

Introduction

Two problems are involved in development of an automated robotic deburring of parts with unknown geometry: 1) the design of an appropriate procedure for a stable metal removal, and 2) the development of a stable control method for tracking the edge of the parts with unknown geometry. Although these two problems for a particular application may be merged together, we separate them in the sense of hardware and control method. This separation allows us to arrive at improved results for both tracking and metal removal. References 1-6 list various effective robotic deburring methods where the knowledge of the part geometry is essential.

Tracking of the Parts

We define tracking a two-dimensional part by a robot as a stable maneuver in which the robot endpoint always remains in contact with the part. Note that the above definition is independent of the type of the geometric knowledge of the part. In fact, the geometric knowledge of the part may not be exactly available prior to the tracking maneuver. The above definition is also independent of the control strategy and it implicitly states the stability of the system and consequently the boundedness of the contact forces.

Figure 1 shows the schematic of tracking an edge of a part. Although the regulation of the contact force in the direction normal to the part surface is an attractive choice in many industrial applications, one is not restrained to do so in tracking a two-dimensional surface.* There are two components in performing the tracking of a part with unknown geometry: the collection of the part geometry and the control method. In this paper, one method of collecting the environment

* One may develop impedance control in the direction normal to the part such that the robot is compliant, and therefore, the normal force remains bounded.
geometry and the robot control method and its stability is described.

A Method for Collecting the Part Geometry. In this section, a practical method of collecting the part geometry based on the measurement of the interaction forces between the part and the robot is described. A two-dimensional force sensor mounted on a roller bearing can provide sufficiently accurate force information for tracking purposes.

Figure 2 shows the detailed schematic of the force sensor assembly mounted on a robot. It is assumed that the part is mounted on a stationary platform. The tracking force imposed on the part by the robot, $t$, consists of two components; the compression force, $t_n$, in the direction normal to the part surface, and the friction force, $t_f$, tangent to the part (Figure 3). If the friction between the roller and part surface is of the Coulomb type, then:

$$ t = \mu t_n $$

(1)

where $\mu$ is the coefficient of dry friction. If the measured forces in the global coordinate frame are $t_x$ and $t_y$, then equality 2 can be achieved by inspection of Figure 3.

$$ \begin{bmatrix} t_x \\ t_y \end{bmatrix} = R \begin{bmatrix} t_n \\ t_f \end{bmatrix} $$

(2)

where

$$ R = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ \sin(\alpha) & -\cos(\alpha) \end{bmatrix} $$

$\alpha$ is the angle between the normal to the part and the $y$ axis in the global coordinate frame. Equations (1) and (2) taken together result in Eq. (3) for the value of $\alpha$.

$$ \tan(\alpha) = \frac{\mu t_x - t_y}{\mu t_x + t_y} $$

(3)

or:

$$ \alpha = \tan^{-1} \left( \frac{\mu t_x - t_y}{\mu t_x + t_y} \right) $$

(4)

By measuring $t_x$ and $t_y$, one can calculate $\alpha$ if $\mu$ is known.** Exact calculation of $\alpha$ requires a precise value of $\mu$. Since the friction between the roller bearing and the part surface is very small, then one can arrive at an approximate value for $\alpha$ from Eq. (5). (The small size of $\mu$ is experimentally verified in the following section, see Figure 6.)

$$ \alpha \approx \tan^{-1} \left( \frac{t_x}{t_y} \right) $$

(5)

In practice, $\mu$ is not a zero quantity and any small perturbation of $\mu$ will cause $\alpha$ to deviate from its value given by Eq. (5). The sensitivity of $\alpha$ in the presence of the perturbation of $\mu$ can be approximated by:

$$ \delta \alpha = \frac{1}{1 + \mu^2} \delta \mu $$

(6)

** Note that an equality similar to Eq. (3) can be derived using the measured forces in the hand coordinate frame rather than the global coordinate frame. For the benefit of consistency throughout the paper, we chose to express the measured forces in the global coordinate frame.
where \( \delta \) represents a small deviation, \( \delta \mu \), for a roller bearing, is a small number which results in a small deviation in \( \alpha \). \( \delta \mu = 0.01 \) results in \( \delta \alpha = 0.57^\circ \) where \( \mu = 0 \). This sensitivity analysis shows that a simple force sensor assembly allows for a relatively accurate part geometric information.

**Control Method for Tracking.** In this section, a control method is developed that allows the robot to track the edge of two-dimensional parts. Employing the above method for calculation of the surface normal, the control method keeps the normal contact force at a constant quantity. The designer is allowed, however, to assign a velocity command in the tangential direction. It is clarified in a later section that the deburring approach described here assigns a value for tangential velocity.

It is assumed that the robot already has a velocity controller. The fact that most industrial manipulators already have some kind of velocity controller is the motivation behind this approach. Also, a number of methodologies exist for the development of robust velocity controllers for direct and nondirect robot manipulators. In general, the endpoint velocity of a robot manipulator that has a velocity controller is a dynamic function of its input trajectory vector, \( e \), and the external force, \( t \). Let \( G \) and \( S \) be two functions that show the robot endpoint velocity in a global coordinate frame, \( v \), is a function of the input trajectory, \( e \), and the external force, \( t \).

\[
v = G(e) + S(t)
\]  

(7)

The motion of the robot endpoint in response to imposed forces, \( t \), is caused by either structural compliance in the robot*** or by the compliance of the velocity controller. Robot manipulators with velocity controllers are not infinitely stiff in response to external forces (also called disturbances). Even though the velocity controllers of robots are usually designed to follow the trajectory commands and reject disturbances, the robot endpoint will move somewhat in response to imposed forces. The sensitivity function, \( S \), maps the external forces to the robot velocity. For a robot with a “good” velocity controller, \( S \) is a mapping with small gain. Nondirect drive robots with high gear ratio also have little sensitivity to external forces. No assumption on the internal structures of \( G(e) \) and \( S(t) \) is made.

**Figure 4** shows one possible example of the internal structure of the model represented by Eq. (7). The robot open loop dynamic equation is \( M(\theta) \ddot{\theta} + C(\theta, \dot{\theta}) + G(\theta) = \tau + J_p \ddot{\theta} \), where \( M(\theta) \), \( C(\theta, \dot{\theta}) \), \( G(\theta) \) and \( J_p \) are the inertia matrix, coriolis, gravity forces and the Jacobian. The driving torque and the external forces on the robot are represented by \( \tau \) and \( t \). With the help of two mappings, \( T_1 \) and \( T_2 \), we define \( \dot{\theta} \) and \( \dot{\theta} \) as the desired velocity and the actual velocity of the robot in the joint coordinate frame. \( P1 \) and \( P2 \) are computer programs that calculate the best estimated values of nonlinear terms in robot dynamics. \( K_v \) is appropriate velocity gain to stabilize the system.7

The system in **Figure 4** with two inputs (\( e \) and \( t \)), and one output, \( v \), can be represented by Eq. (7). In the analysis of the tracking controller, we employ Eq. (7) as

***In a simple example, if a remote center compliance (RCC) with a linear dynamic behavior is installed at the endpoint of the robot, then \( S \) is equal to the reciprocal of stiffness (impedance in the dynamic sense) of the RCC.
the basic dynamic equation of the robot that already has a velocity controller. The type of velocity controller is not of importance at this stage. Regardless of the kind of controller, one can always consider the closed loop system dynamics in terms of the structure of Eq. (7).

Equation (7) represents an input/output functional relationship. It allows us to incorporate the dynamic behavior of all the elements of the robot. Many industrial robot manipulators already have some kind of velocity controllers. Within the bandwidth of the velocity control, \( (0, \omega_c) \), the dynamic behavior of the robot is uncoupled. In other words, for all frequencies in \( (0, \omega_c) \), a command in a particular direction will generate a velocity in the commanded direction only. Outside of the robot closed loop bandwidth, the robot dynamics are coupled and a velocity command in a particular direction, in general, may develop velocity deviation in some or all directions.

Regarding the above practical issue, we assume \( G \) and \( S \) are uncoupled functions within \( (0, \omega_c) \); \( G_n \) and \( S_n \) represent the robot dynamic behavior in the direction normal to the part, while \( G_t \) and \( S_t \) show the dynamics of the robot in the direction tangent to the part. Figure 5 shows the dynamics of the robot and part in the direction normal to the part. \( E_n \) represents the dynamic behavior of the part and sensor in the direction normal to the part. In the simplest case, one can think of \( E_n \) as the stiffness of a spring that could possibly model the part stiffness.

The compensator, \( H_n \), is considered to operate on the contact force, \( t_n \). The reference signal, \( t_o \), represents the desired normal contact force. The compensator output signal subtracted from \( t_o \) is used as the normal input command signal, \( e_n \), for the robot velocity controller.

There are two feedback loops in the system; the inner loop (which is the natural feedback loop), shows how the contact force affects the robot in a natural way when the robot is in contact with the part. The outer feedback loop is the controlled feedback loop. When the robot and the part are in contact, then the value of the contact force and the endpoint velocity of robot are given by \( t_n \) and \( v_n \), where the following equations are true:

\[
\begin{align*}
    v_n &= G_n (e_n) - S_n (t_n) \\
    t_n &= E_n (\int v_n) \\
    e_n &= t_o - H_n t_n
\end{align*}
\]  

If the operators in Eqs. (8), (9), and (10) are linear, the transfer function in Eq. (11) can be obtained to represent the force in the normal direction.

\[
t_n = E_n (s + S_n E_n + G_n H_n E_n)^{-1} G_n t_o
\]  

Impedance of the part in the normal direction, \( E_n \), is a large quantity in comparison with the other parameters in the system. If \( E_n \) approaches infinity, then Eqs. (12) and (13) represent the value of \( t_n \) and \( v_n \):

\[
t_n = (S_n + G_n H_n)^{-1} G_n t_o
\]  

\[
v_n = 0
\]

Note that \( S_n \) and \( G_n H_n \) add in Eq. (12) to develop the total compliancy in the system. \( G_n H_n \) represents the electronic compliancy in the robot, while \( S_n \) models the natural hardware compliancy (such as RCC or the robot structural compliancy) in the system. A large value for \( H_n \) develops a compliant robot, while a small \( H_n \) generates a stiff robot. Reference 8 describes a micro manipulator in which the compliancy in the system is shaped for metal removal application. Equation (12) also shows that a robot with good tracking capability (small gain for \( S_n \)) may generate a large contact force in a particular contact. One cannot arbitrarily choose

---

\[ ^{\dagger} \text{Equation (11) can be rewritten as } t_n = (sE_n + S_n + G_n H_n)^{-1} G_n t_o. \] Note that the part admittance (1/impedance in the linear domain), \( E_n^{-1} \), the robot sensitivity (1/stiffness in the linear domain), \( S_n^{-1} \), and the electronic compliancy, \( G_n H_n \), add together to form the total sensitivity of the system. If \( H_n = 0 \), then only the admittance of the environment and the robot add together to form the compliancy for the system. By closing the loop via \( H_n \), one can add to the total sensitivity of the system.
large values for $H_n$; the stability of the closed-loop system of Figure 5 must be guaranteed. To guarantee the stability of the closed-loop system in the linear case, $H_n$ must be chosen such that:

$$| H_n | < | s G^* (s_n/s + 1/E_n) |$$

(14)

where $| . |$ denotes the magnitude of the transfer function. The smaller the sensitivity of the robot manipulator, the smaller $H_n$ must be chosen. Also from inequality 15, the more rigid the part is, the smaller $H_n$ must be chosen. In the “ideal case”, no $H_n$ can be found to allow an infinitely rigid robot ($S_n = 0$) to interact with an infinitely rigid part ($E_n = \infty$). In other words, for stability of the system shown there must be some compliance either in robot or in the part. RCC, structural dynamics, and the tracking controller stiffness form the compliance on the robot.

An XYZ table (Figure 10) was employed as a simple two-dimensional robot to experimentally verify the effectiveness of the tracking method. The XYZ table holds the part to be tracked, while a stationary platform holds the force sensor and the roller bearing. The XYZ table is powered by two DC motors via a two screw mechanism. The screws are double-helix and 0.2 inch per revolution. Each axis of the table has a simple PID velocity controller. $H_n$ was chosen small enough to guarantee inequality 14. Figure 6 shows the experimental values for normal and tangential forces, $f_n$ and $f_t$ for a period of two seconds.

### Deburring Strategy

This section focuses on the deburring mechanics and its required control approach and includes an analysis of the deburring process model, and the required control strategy for metal removal. The deburring control strategy is independent of the tracking control.

**Process Dynamic Model.** This section describes several quantitative and geometric properties of burrs formed in the cutting process. These properties, which are independent of the control algorithm, lead to the development of a simple dynamic model for the cutting process. The control algorithm used in the next section is benefited by this dynamic model.

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:

$$MRR = (A_{chamfer} + A_{burr}) V_{tool}$$

(15)

In the deburring process, the cutting force in the tangential direction is proportional to MRR. For a given constant feedrate, $V_{tool}$, the tangential force varies very significantly with variation of the burr size; thus, whenever the rotary file encounters a large burr, the tangential force increases dramatically. For a given constant feedrate, the normal force stays relatively constant regardless of burr size variation. Figure 7 shows the proportionality of the tangential cutting force, $f_t$, with MRR when an edge with 45° chamfer is cut.

$$f_t = K \times MRR$$

(16)

$K$ depends on the material properties, while MRR is a geometric quantity.

For a given depth of cut (0.055") on an edge without a burr, the feedrate was varied and the MRR was measured. As shown in Figure 7, the cutting process requires some minimum tangential force to pene-

---

†† The stability criterion for interaction of a multivariable nonlinear robot with a part with nonlinear dynamic behavior has been described in Reference 10.
trate the material. The operating point for the experiments is along the linear section of the plot in Figure 7. Since \( A_{\text{change}} \) is constant in this experiment, the tangential force is therefore proportional to the feedrate. The faster the speed of the tool along the edge is, the larger the tangential contact force will be.

The slope of the line in Figure 7 (1016 nt/grams/sec) represents the proportionality of the tangential force with the MRR. Considering the specific mass of steel as 7 grams/cm\(^3\), the slope of the line equal to 7112 nt/cm\(^3\)/sec and represents the proportionality of the contact force with the volumetric MRR. Taking into account the projected tangential area of 0.0098cm\(^2\), the proportionality of the tangential cutting force with the velocity along the edge is 69.8nt/cm/sec. It requires 69.8nt of tangential force to cut along the edge with the speed of 1 cm/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, there is an expected increase in the tangential force when the cutting tool encounters a burr along the edge of the part.

**Control Strategy for Deburring.** This section is devoted to the control of a robot for deburring tasks only. Suppose the cutting tool is being moved with constant speed by an industrial robot along the edge of a part, then the cutting force will vary significantly because of the variation of the burr size. This cutting force can be resolved into two orthogonal directions as shown in Figure 8. If the contact force is large due to the size of the burr, a separation of the robot from the part will occur. It is desirable to develop a self-tuning strategy such that the cutting force in the cutting process becomes small when the cutter encounters a burr. A small force guarantees that the cutter 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 down the surface to the commanded trajectory depicted by the dashed line in Figure 8. It is intuitive to design a position control mechanism for the manipulator with a small sensitivity in the normal direction and a force control in the tangential direction.

A trajectory control with small sensitivity in the normal direction causes the endpoint of the grinder to reject the cutting forces and stay very close to the commanded trajectory (dashed-line). We define the sensitivity as the ratio of the robot motion to the normal cutting force. 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.\(^{12}\)

As previously described, 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 endpoint 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 (Eq. (16)).

It is desirable 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 cutting force is maintained in the tangential direction. Two problems are associated with large cutting forces in the tangential directions: 1) the cutting tool may stall (if it does not break), and 2) a slight deflection may develop in the endpoint 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, \( \omega_s \). The frequency range of the burr seen from the end-effector is represented by, \( \omega_p \). The faster the robot endpoint travels along the edge of the part, the wider \( \omega_p \) will be. The bandwidth of the control system in the tangential direction must be larger than \( \omega_p \). In other words, one must travel with an average speed along the edge of the part such that \( \omega_p \) 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 9 illustrates the architecture of the closed-loop control system for the robot in the tangential direction. The detailed description of each operator in Figure 9 is similar to the one shown in Figure 4.

\( G_r \) is the transfer function (or a mapping in the nonlinear case) that represents the dynamic behavior of the robot with a velocity controller in the tangential direction. The input to \( G_r \) is the input velocity, \( e_r \). The robot velocity in the tangential direction is represented by \( v_r \). \( G_r \) can be experimentally or analytically calculated. Note that \( G_r \) 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 \( G_r \). The bandwidth of \( G_r \) is represented by \( \omega_s \).

\( S_r \) is the sensitivity transfer function (or a mapping in the nonlinear case), and represents the relationship between the external force on the endpoint and the endpoint 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, \( S_r \) must be quite "small". The notion of "small" can be regarded in the singular value sense when \( S_r \) is a transfer function matrix. \( L_\infty \) norm can be considered to show the size of \( S_r \) in the nonlinear case. \( S_r \) shows the advantage of velocity control.

The dynamic behavior of the part is represented by \( E_r \). In the linear case, \( E_r \) has been measured from the slope of the plot in Figure 7 and its value is equal to 69.8n/sec. In general, one can consider a nonlinear function to characterize \( E_r \).

\( H_r \) is the compensator to be designed. The input to this compensator is the tangential deburring force. The compensator output signal is subtracted from the input tangential velocity, \( v_r \), to give the error signal, \( e_r \).
as the input velocity for the robot manipulator in the tangential direction. The value of the tangential force and the endpoint tangential velocity of the robot are given by Eqs. (17) and (18).

\[ d_i = E_i (1 + S_i E_i + G_i H_i E_i)^{-1} G_i V_o \]  (17)

From Figure 9, \( d_i = E_i V_i \), therefore:

\[ v_i = (1 + S_i E_i + G_i H_i E_i)^{-1} G_i V_o \]  (18)

The goal is to choose a class of compensators, \( H_i \), to shape the impedance of the system, \( E_i (1 + S_i E_i + G_i H_i E_i)^{-1} G_i \), in Eq. (17). The small value for \( H_i \) in a particular direction implies a very stiff velocity control system. In the limit, when \( H_i \) is chosen to be zero in a particular direction, the system behaves as a velocity control in that direction. When \( H_i \) is chosen to be a large number, the system will be very compliant in tangential direction and small contact forces will be generated. In the deburring process, it is planned to modulate \( H_i \) such that it has a large value in the direction tangential to the part while the system is stable.

To guarantee the stability of the closed-loop system in the linear case, \( H_i \) must be chosen such that:

\[ |H_i| < |G_i^{-1} (S_i + 1/E_i)| \]  (19)

where \(| . |\) denotes the magnitude of the transfer function. The smaller the sensitivity of the robot manipulator, the smaller \( H_i \) must be chosen. Also from inequality 19, the more rigid the part is, the smaller \( H_i \) must be chosen.

### Merging the Deburring and Tracking

The \( XY \) table in Figure 10 is used to employ the above tracking and deburring methods in deburring the parts with unknown geometry. 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 with the robot while the part is on a stationary platform. Reference 8 describes an active end-effector that can be held by commercial robot manipulators for such application.

As seen in Figure 10, two force sensors are used in this operation. One force sensor is installed on the tool holder for measurement of tracking force, \( t \), while another force sensor is installed under the part for measurement of the deburring force, \( d \). Note that the use of two sensors in this architecture is necessary. The normal deburring force cannot be used in tracking algorithm. If the normal deburring force is used in tracking algorithm, the tool will follow the contour of the burr and a rounded burr will be developed.

The \( XY \) table is interfaced to a micro computer for control. The control algorithms of the tracking and deburring were implemented on the \( XY \) table via the \( \mu \)-computer. \( H_i \) and \( H_o \) are chosen to satisfy inequalities 14 and 19. Because of the lead screw mechanism in the \( XY \) table drive, \( S_i \) and \( S_o \), the sensitivity of the \( XY \)

![Figure 10](image)

The \( XY \) Table Used as a Two-dimensional Robot to Maneuver the Part

![Figure 11](image)

Frequency Response of \( G_i \)
The objective of this experiment is to decrease the size of the cutting forces in an edge deburring when the above method control is employed to control the $XY$ table. The edge of the sample part has been filed to produce step burrs as shown in Figure 12.

Figure 13 shows the tangential and normal forces when no force control is employed in the tangential direction. The grinder is driven with constant velocity along the edge of the part. As seen in Figure 13, once the grinder encounters the burr, the tangential force increased to 25 nt and the deburring tool stalled.

Figure 14 shows the tangential and normal forces when a force control strategy according to Figure 9 is employed in deburring the same size burr (depth of cut $= .045^\circ$). $H_f$ in the direction normal to the part is chosen...
to be zero. \( H_1 \) in the direction tangential to the part is chosen to be a large number while satisfying inequality 19. The commanded tangential force is 5 nt and the average speed is 0.088 in/sec.

Figure 15 shows the tangential and normal force with the same commanded force in the tangential direction when a burr with the depth of cut of .06" is used. Since the tangential force remains constant at 5 nt, the average speed of the system decreased 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 also constant. The ratio of the velocities \( \frac{0.088}{0.057} = 1.6 \) is inversely equal to the tangential area ratio \( \frac{0.06}{0.045} \) = 1.7.

Concluding Remarks

Two problems have been addressed in this paper: tracking the two-dimensional part contour, and control of the metal removal process. The use of two sensors in this deburring method is necessary. The tracking control employs the force measured by a force sensor to find the normal to the part surface, while the deburring algorithm uses another set of contact forces (cutting forces generated by the cutter) to develop a stable metal removal. One cannot use the normal deburring force in tracking algorithm. If the normal deburring force is used in tracking algorithm, the tool will follow the contour of the burr and a rounded burr will be developed. A set of experimental results have been carried out to verify the theoretical concepts.

Acknowledgement

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

References


Author Biography

H. Kazerooni received a M.S. in mechanical engineering from the University of Wisconsin, Madison in 1980, and a M.S.M.E. and Sc.D. degrees in mechanical engineering from the Man-Machine Systems Laboratory of the Massachusetts Institute of Technology, Cambridge, in 1982 and 1984, respectively.

From 1984 to 1985, he was with the Laboratory of Manufacturing and Productivity at the Massachusetts Institute of Technology as a Post Doctoral Fellow. He is currently an Assistant Professor in the Mechanical Engineering Department at the University of Minnesota, Minneapolis.