Automated Roboting Deburring Using Electronic Compliancy; Impedance Control

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Abstract

A new strategy has been developed for precision deburring and grinding to guarantee burr removal while compensating for robot oscillations and small uncertainties in the location of the part relative to the robot. This problem has been posed as a frequency domain control problem. Electronic compliancy (impedance control) is demanded as an "adaptive" mechanism to satisfy the requirements of this new strategy. This paper examines the development and implementation of impedance control methodolgy (7,8,9,10,16) on an active end-effector(15) (or the whole robot if it is possible) for precision deburring and grinding tasks.

Nomenclature

A_{burr}	the cross sectional area of the burr
$A_{chamfer}$	the chamfer area
C_n , C_t	damping factors in the normal and tangential direction
F_n, F_t	contact forces in normal and tangential directions
J_n, J_t	Intertia in the normal and tangential direction
K_n , K_t	stiffness in the normal and tangential direction
M	grinder mass
MRR	material removal rate
R_{tang}	$A_{burr}/A_{chamfer}$ (Tangential Area Ratio)
V_{tool}	Tool Velocity
X_n , X_t	robot end point deflection in normal and tangential directions
ω_b	frequency range of the burr seen by the robot
ω_r	frequency range of oscillations of the robot

1. Introduction

Since deburring and grinding are finishing processes, parts at this this stage in production have their highest value-added value. 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 the 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 requires a high quality finish also. According to the above points, the deburring and grinding of machined parts is a major area of concern in improving manufacturing. 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 (1,4,6,17,19,20,22,23 and 25) contain valuable contribustions from previous research. The basic ideas of these can be itemized as follows:

I. Robotic deburring and grinding has mostly been studied as a trajectory following task. Although robotic deburring is a task with final geometrical specifications, the contact forces in the normal and tangential directions are a fundamental part of the process. The necessity of control on the normal and tangential forces in addition to geometrical surface finish specifications, brings the concept of impedance control into our consideration. Note that the objective is not to use force control (18,24) techniques.

II. Adaptive electronic compliancy (impedance control) has not been considerd as an aid in developing appropriate contact forces for deburring.

III. Attention has mostly been focused on the programming and integration of the process rather than the dynamics of both the process and the robot together.

IV. The design issues of an active end-effector (15) (or any adaptive system with the capability of modulating its impedance) has never been considered.

2. Geometric and Qualitative Model of the Burr

In this section we describe some qualitative and geometric properties of burrs formed in the cutting process. This information can be found in references (3), (13) and (14). However, for continuity of the subject, we mention these properties briefly.

Burrs are formed by many manufacturing processes and the type of burr formed depends directly on the process used and the prevailing conditions. Burrs can be a direct result in the application of cutting tools. Burrs can also result from tooling-imperfections in casting and forming. Although the focus of this paper is mostly on the deburring of edges, the results are applicable to other burrs also.

The size and orientation of the burrs on a part is completely random in nature. A dimensional model of a burred 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 0.25 to 0.75 mm (0.010" to 0.030"), and a thickness of 0.025 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.

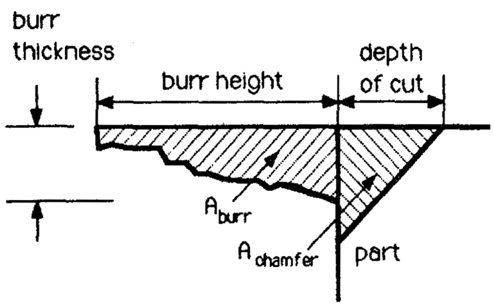


Figure 1: Typical Profile of a Burr on a Part Edge

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:

$$MRR = (A_{chmfer} + A_{burr}) V_{tool} \quad (1)$$

$$MRR = A_{chamfer} (R_{tang} + 1) V_{tool} \quad (2)$$

where: $R_{tang} = A_{burr} / A_{chmfer}$

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: feed-rate, 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 any dynamic behavior; they only emphasize the proportionality of MRR with feed rate, depth of cut and chamfer area.

R_{tang} can vary in process from zero for sharp corners, to 0.2 for average burrs, and to the worst case ratio of 2.0 depending on the A_{chmfer} chosen. Therefore MRR for a given velocity and a desired constant chamfer can vary up to 200% depending the size of the burr. Since, the contact force is proportional to material removal rate (MRR), large variations are expected in the components of the cutting force due to variations in the burr area for a given velocity (feedrate) and chamfer area.

A three dimensional geometric model of a burr, which includes the full geometry of the conic bit, as seen in Figure 2, is more useful for this work. The cutting force, can be resolved into two vector components of interest: the tangential force (in the direction of the tool velocity) and the normal force.

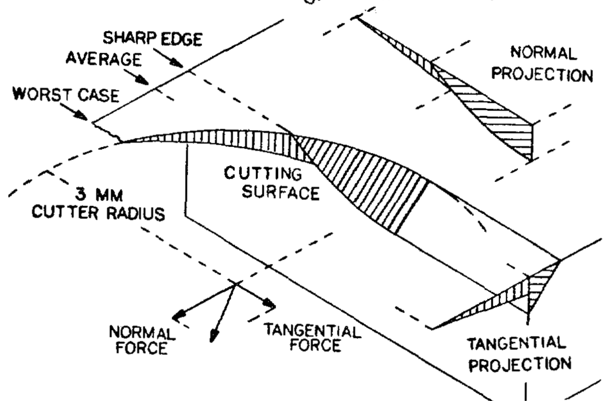


Figure 2: Cutting Surface Area, 45 Degree Conic Mill

The cutting force is largely a function of the average surface area of the cut for a given feedrate. The projected areas, as seen in the model, are simply geometric functions of the intersection between the part corner, the burr, and the milling cone. Using this model, the area ratio, or the projected burr area divided by the projected chamfer area, will indicate the effect of burr size on the component of the cutting force normal to that area. 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. To summarize the results of this section:

1) For a given constant feedrate the tangential force varies very significantly with variation of the burr size; in other words 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 varaition.

The above two results have been verified experimentally which will be discussed in Section 6. Suppose the cutting tool is being moved by an industrial robot, the force which is imposed on the end point of robot will vary significantly due to the variation of the burr size if the robot is moving with constant speed along the edge. 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.

3. Robot Position Uncertainties

In this section, we frame the position uncertainties of exsiting robots mathematically in the frequency domain. The positional accuracy of existing industrial robots is generally poor. For example, the General Electric P50 robot used in deburring tests has a limited programmable resolution of 0.25 mm (.01"). Furthermore, the robot end-point position at a programmed point is characterized by a low frequency periodic motion with a peak-to-peak amplitude of 0.1 to 0.2 mm. Based on total positional uncertainties of about 0.35 mm, the P50 by itself, is unsuitable for precision deburring tasks. There are also some positional uncertainties in fixturing the part.

A common solution to this problem involves the addition of compliant elements between the robot and the deburring tool. Considerable work has been done using compliant deburring end-effectors (2,3 and 21). The device features compliance in two orthogonal directions in the form of replaceable springs and fluid dampers. In fact, RCC (Remote Center of Complinace) was invented for compensation of the robot position uncertainty in a passive fashion. Figure 3 shows an example of the passive end-effector (3). Although we do not intend to use a passive compliant end-effector as a tool to compensate for the robot position uncertainties, we analyze its dynamic behavior to understand the requirements for compensation of the robot position uncertainties. The dynamic behavior of the passive end-effector in the direction normal to the part, can be approximated by a second order dynamic equation as:

$$\delta F_n(s) = (Ms^2 + C_n S + K_n)\, \delta X_n(s) \qquad (3)$$

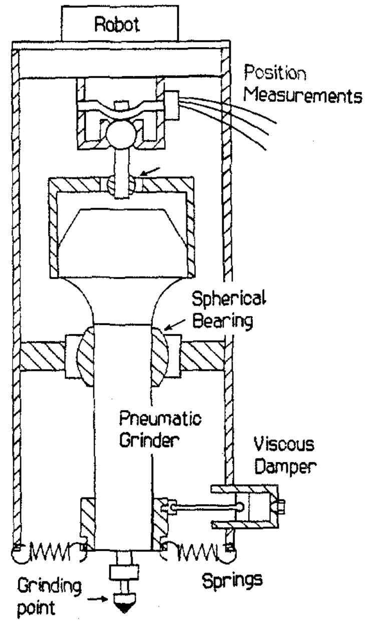
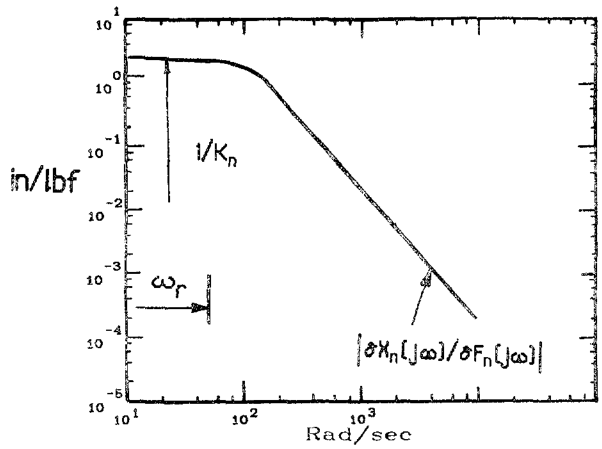


Figure 3: A Passive Compliant End-effector

Where M is the tool mass, C_n and K_n are the damping and the spring stiffness of the end-effector in the normal direction respectively, and s is the Laplace operator ($s=j\omega$). Figure 4 depicts $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ for some frequency range. For all frequencies $0<\omega<\sqrt{K_n/M}$, one can approximate the dynamic equation of the end-effector as $|\delta F_n(j\omega)| \approx K_n\, |\delta X_n(j\omega)|$. So, if the position uncertainties of the robot manipulator in the normal direction have a frequency spectrum of less than $\sqrt{K_n/M}$, the normal contact force variation will be $K_n|\delta X_n(j\omega)|$. If K_n is chosen to be small (large compliancy), then $\delta F_n(j\omega)$ will be small in the presence of a fairly large $\delta X_n(j\omega)$. Note that $\delta X_n(j\omega)$ is the robot positional uncertainty (robot oscillations, robot programming errors, fixturing errors) for which compensation must take place. Compensation of robot position uncertainties by compliant end-effectors requires that M be chosen such that $\sqrt{K_n/M} > \omega_r$, where ω_r is the frequency range of the robot oscillations. The choice of M is limited by the grinder size. If the end-effector bandwidth ($\sqrt{K_n/M}$) is not wider than the frequency range of the robot oscillations, then large contact forces in the normal direction would occur due to other terms such as Ms^2 and $c_n s$.

Two questions may be raised: 1) What compliancy is needed in the normal direction and in the tangential direction in the deburring process? 2) Does the prescribed high compliancy for compensation of robot position uncertainties conflict with the required compliancy for the deburring process? These questions are answered in the following section.

In summary, the compensation of the low frequency uncertainties in the robot position requires large compliance in the end-effector in the direction normal to the part.



4:The Required Dynamic Behavior of the End-effector in the Normal Direction for Oscillation Compensation of the Robot.

4. Control Strategy

In this section, we propose a new approach for deburring using a robot. First, we assume there are no uncertainties in the robot position. After understanding the requirements for deburring by a "perfect" robot, we incorporate the robot uncertainties (discussed in Section 3) in our analysis.

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 5. It is intuitive to design a control mechanism for the manipulator with a large impedance (small compliance) in the normal direction and a small impedance (large compliance) in the tangential direction. We define impedance as the ratio of the contact force to the end-effector deflection as a function of frequency. For example, the impedance of the end-effector in the normal direction is $Ms^2 + C_n s + K_n$.

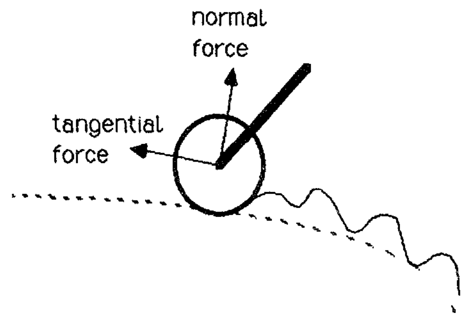


Figure 5: Deburring an Edge

A large impedance in the normal direction causes the end-point of the grinder to reject the interaction forces and stay very close to the commanded trajectory (dashed-line). The larger the impedance of the end-effector 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 impedance in the normal direction. As described in Section 2, 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 [5]. 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 small impedance value in the tangential direction. If a designer does not accommodate the interaction forces by specifying a small stiffness value in the tangential direction, the large burrs on the surface will produce large contact forces 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), and 2) a slight deflection may develop in the end-point position in the normal direction, which might exceed the desired tolerance. A small value for the impedance in the tangential direction (relative to the impedance in the normal direction) guarantees small contact force in the tangential direction. 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* ω_b. ω_b is the frequency range of the burr seen from the end-effector. The following equalities summarize the dynamic characteristics, required for the deburring with a perfect robot.

$$|\delta X_n(j\omega)/\delta F_n(j\omega)| \triangleq \text{very small for all } \omega \in \omega_b$$

$$|\delta X_t(j\omega)/\delta F_t(j\omega)| \triangleq \text{very large for all } \omega \in \omega_b$$

From the analysis on the compensation of the robot oscillation in Section 3, $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ must be large for all $0<\omega<\omega_r$ to compensate for the uncertainties in the robot position. Choosing a large impedance conflicts with the required impedance to compensate for robot oscillations. The compensation for robot position uncertainties demands a low impedance (large compliance) in the normal direction, while a large impedance is required for deburring purposes. If one designs an end-effector with the dynamic characteristics shown in Figure 6, then both requirements can be satisfied. As shown in Figure 6, $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ is very large for all $\omega \in \omega_r$ and very small for all $\omega \in \omega_b$. While a large $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ in $(0,\omega_r)$ does not let the robot oscillations develop a large variation in the normal contact force, a small $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ in ω_b will cause the end-effector to be very stiff in response to the burrs. The following is a summary of the characteristics of the end-effector in the normal direction.

- $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ must be large for all $\omega \in \omega_r$
- $|\delta X_n(j\omega)/\delta F_n(j\omega)|$ must be small for all $\omega \in \omega_b$
- $\omega_r < \sqrt{K_n/M} < \omega_b$

Figure 6 also shows the dynamic behavior of the end-effector in the tangential direction. For all $\omega \in \omega_b$, $|\delta X_t(j\omega)/\delta F_t(j\omega)|$ is large to guarantee the deburring requirements. Note that $|\delta X_n(j\omega)/\delta F_n(j\omega)| << |\delta X_t(j\omega)/\delta F_t(j\omega)|$ for all $\omega \in \omega_b$. It is <u>impossible</u> to design and build a passive end-effector with the dynamic characteristics shown in Figure 6. This is because of the role the constant mass of the tool plays in the dynamic behavior of the end-effector. Since the mass of the grinder is a constant parameter in the dynamic equations of the end-effector in both directions, the only possible dynamic behavior for a passive end-effector is of the form given in Figure 7. For a given set of K_n and K_t in both directions, one cannot choose arbitrary natural frequencies in both directions. The natural frequencies (or bandwidths) for a passive end-effector are fixed approximately at $\sqrt{K_n/M}$ and $\sqrt{K_t/M}$.

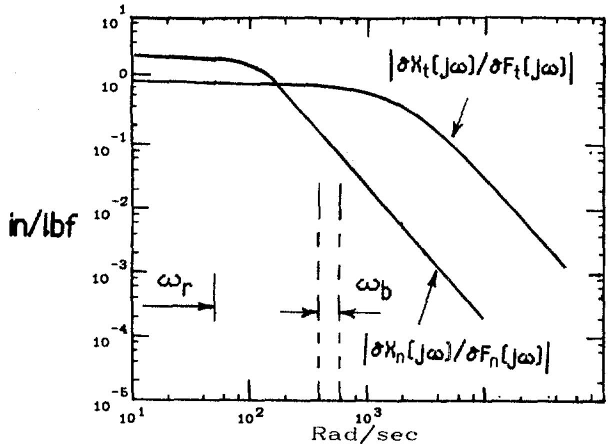


Figure 6: The Ideal Dynamic Behavior of the End-effector

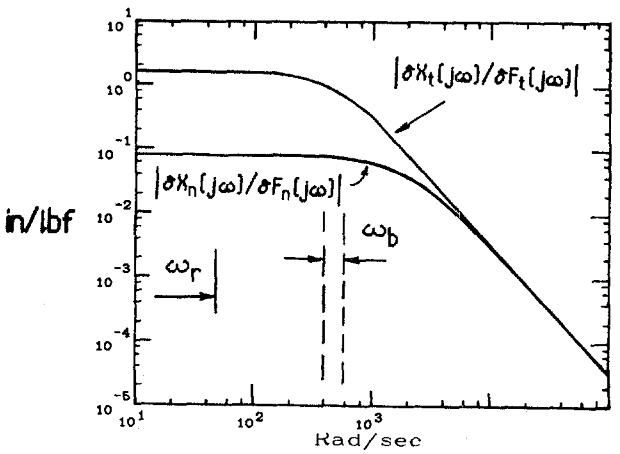


Figure 7: The Achievable Dynamic Behavior of a Passive End-effector

The dynamic behavior of the end-effector in both directions at high frequencies is equal. As shown in Figure 7, K_n and K_t are chosen very large and very small respectively, to guarantee the requirement for deburring. However, K_n must be small enough such that the variation in the position of the robot does not develop a sizable variation in the normal contact force. This is a dilemma which is solved in Section 5 by "impedance control" (7,8,9,10,16). This method is the only method able to develop electronically a dynamic behavior such as those given in Figure 6. The impedance control method will guarantee adaptive stiffness will be achieved for a system for an arbitrary (but bounded) frequency range.

In summary, we examine the design rules and the resulting dilemma. The low stiffness in the normal direction causes the system to be robust relative to the robot oscillations, robot programming inaccuracies, and fixturing errors in all $\omega \in \omega_r$. To deburr with robots, low and high impedances are necessary in the tangential and normal directions for all $\omega \in \omega_b$. The large stiffness of the end-effector in the normal direction causes the end-effector to reject the contact forces and stay very close to the commanded trajectory. The necessity of a large K_n conflicts with the requirement for compensation of the robot oscillations. The following section is devoted to describe "impedance control".

5. Impedance Control

For a rigorous and mathematical explanation of impedance control, see references 9, 10 and 16. A simple and brief definition of impedance control is given in this section for a planar mechanism. The design objective is to provide a stabilizing, positioning compensator for the system (an active end-effector or the whole robot if it is possible) such that the ratio of the position of the closed-loop system to the interaction force is constant within a given operating frequency range. The above statement can be mathematically expressed by equations 4 and 5.

$$(J_n s^2 + C_n s + K_n)\, X_n(s) = F_n(s) \qquad (4)$$

$$(J_t s^2 + C_t s + K_t)\, X_t(s) = F_t(s) \qquad (5)$$

Note that the above two equations only represent the desired behavior for the end point motion of the grinder, and they do not imply any control technique. These two equations are called the target impedance. The stiffness parameters are the designer's choice; depending on the application, the parameters contain different values for each direction. By specifying K_n and K_t, the designer governs the behavior of the system in constrained maneuvers. Large values of K_n and K_t imply large interaction forces. A small value for K_n or K_t will allow a considerable amount of motion in the system for a reaction to interaction forces. To clarify the contribution of J_n, J_t, C_n, C_t, consider Figure 8, which is a plot of equation 4. If C_n is the only parameter that guarantees a stable and slightly over-damped system, then it can be claimed that J_n is the only effective parameter used in increasing or decreasing the bandwidth, ω_o, for a given K_n. In other words, for a given K_n, one can choose a J_n such that X_n/F_n remains close to $1/K_n$ for all $0<\omega<\omega_o$; therefore J_n is the only effective parameter in increasing and decreasing bandwidth, ω_o, for a given K_n.

C_n can be chosen to guarantee stability for a given set of K_n and J_n. Equations 4 and 5 are the parameterizations for the set of performance specifications (stiffness, bandwidth and stability). For

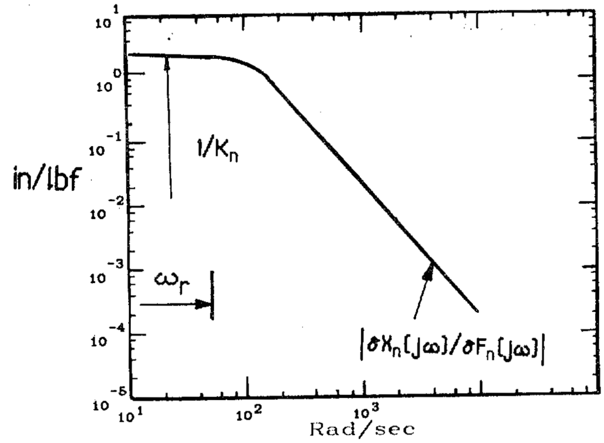


Figure 8: Plot of $\delta X_n/\delta F_n$ for Some Bounded Frequency Range.

example, in the deburring problem, K_t and K_n must be chosen such that $K_t<K_n$. Selection of K_t and K_n depends on parameters such as depth of cut, surface finish specification, part stiffness and the desired speed along the path. The desired bandwidth depends on the frequency spectra of the burrs on the surface and the speed of the robot along the path. For a given pair of K_n and K_t, J_n and J_t can be chosen so that the desired bandwidths can be guaranteed in both directions. After choosing J_n and J_t, C_n and C_t can be chosen to guarantee the stability. By specifying J_n, J_t, C_n, C_t, etc., one can modulate the impedance of the system. If the end-effector is in contact with the environment and a new reference point is commanded (e.g., by a supervisory program), then, since the parameters of the impedance in equations 4 and 5 are under control, the interaction forces will also be under control. References 18 and 24 explain other forms of compliance in terms of force control which is quite different from the impedance control.

6. Experimental Setup

An experiment was conducted to verify the feasibility of using "impedance control" in robotic deburring. The principal issue in this experiment is to investigate if "impedance control" methodology can genuinely and reliably meet the deburring specification mentioned in section 4 in the absence of position uncertainties such as robot oscillation. The experiments to validate the use of impedance control to consider the robot position uncertainties are not completed yet. Although we acknowledge the influence of many side variables in the deburring process Our concern is to study the practicality of a "clean impedance control" in metal removing process without introducing extra and unrelated factors in the experiment. Therefore we employed a high precision and fast XY table for planar maneuvering. This eliminates the uncertain position issue associated with the robot oscillation and reaction forces. Figure 9 shows the experimental set up.

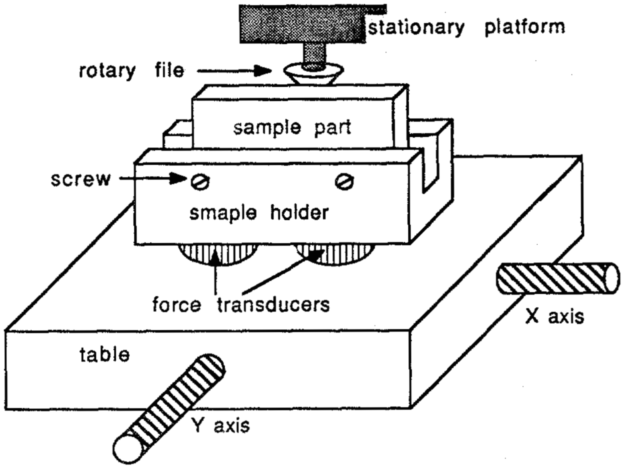


Figure 9: The Experimental Setup

The workpiece to be deburred is mounted on the XY table for maneuvering while the grinder is held vertically by an 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. Figure 10 show the sample holder to hold a rectangular sample part. 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. Reference 15 describes an active end-effector that can be held by commercial robot manipulators. One can develop electronic complinacy (16) on this active end-effector. Our experimental set up is developed only to understand the nature of forces in cutting mechanics under influence of "impedance control" methodology. The XY table is interfaced to an IBM AT 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.

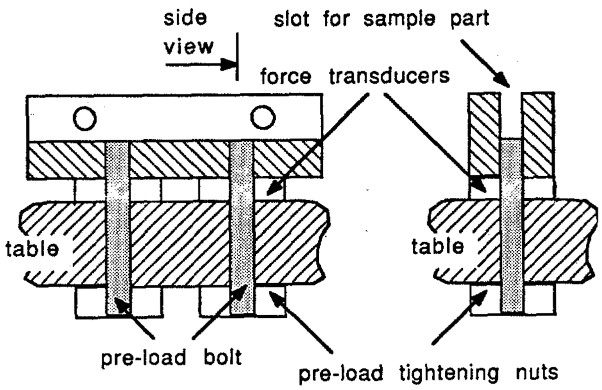


Figure 10: A Fixture to Hold the Straight Edge Sample Part

6. Experiment

We start with the simplest experiment. The objective of this experiment is to substantiate the size of the cuting forces in a straight edge deburring when "impedance control" is employed to control the XY table. The parts to be deburred are rectangular aluminium 2"×5"×.25" as shown in figure 11.

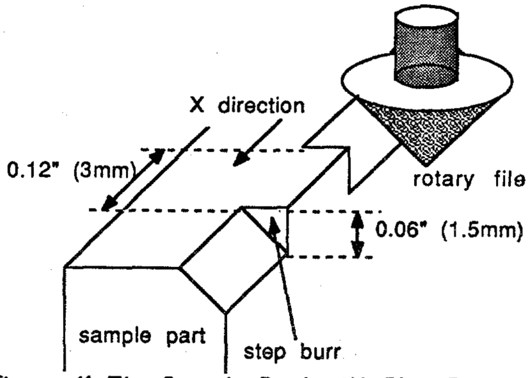


Figure 11: The Sample Part with Step Burr

The edge of the sample part has been filed to produce step burrs as shown in Figure 11. The XY table is commanded to move in X direction to encounter the burr with constant feedrate of .036 in/sec. Figure 12 shows the normal and tangential forces when constant speed control is employed to travel accross the edge of the burr (no impedance control and the force sensors are off). When the grinder encounters the burr, the tangential force increases while the normal force is almost constant. Since the feedrate remains almost constant, the tangential force increases proportional to the material removal rate.

In the next set of experiments, impedance control was employed to control the XY table motion. A large and a small impedance were considered in normal and tangential directions to the part. Figure 13 shows the normal and tangential forces. When the grinder encounters the burr, the table slows its feedrate to grind the burr. It takes about 5×0.84 seconds to deburr the burr, while in the previous example the deburring takes about 4×0.84 seconds. The average tangetial force does not increase as much as in the previous experiment. This is because a small value is chosen for the impedance of the table in the tangential direction.

7. Conclusion

An automated deburring procedure using a robot manipulator is considered in this paper for the removal of burrs in the presence of robot oscillations and bounded uncertainties in the location of the robot end-point relative to the part. To remove the burr, high and low impedances are required in the tool-holder in the normal and tangential directions, respectively, for

Figure 12: The Tangential and Normal Forces in the Deburring Process with Constant Feedrate 0.036in/sec

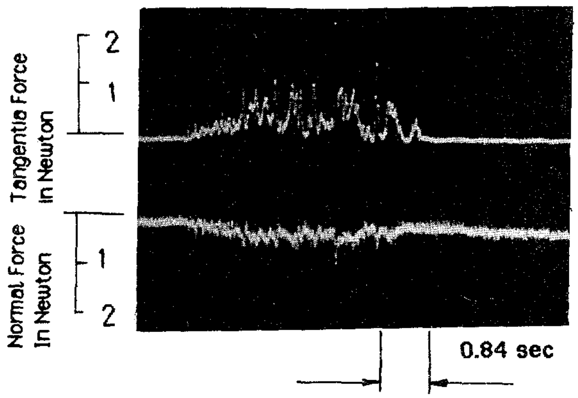


Figure 13: The Tangential and Normal Forces in the Deburring When Impedance Control is Employed

the frequency range that burrs are seen by the robot. To compensate for robot oscillations and positional uncertainties, a low impedance is required for the end-effector in the normal direction for the frequency range of the robot oscillations. The above two requirements for deburring and oscillation compensation, establish a design rule for control strategy for deburring. A passive system cannot provide the above two design rules. This is because of the role the constant mass of the grinder plays in the dynamic behavior of the end-effector. Impedance Control is chosen to satisfy the design rules for robotic deburring and grinding. This paper examins the development and implementation of impedance control methodology to precision deburring. Some of the theoretical results have been verified experimentally.

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