FORCE-CONTROLLED ROBOTIC DEBURRING

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Abstract. In this paper a three-step *active* deburring strategy is proposed based on force feedback control. Strategies for automatic contour following are developed to identify unknown workpiece contours, to automatically generate desired robot motions, and to detect unknown burr sizes. Under the *active* deburring strategy burr size variations are identified through contour following and different sizes of burrs are removed with a specification of a variable desired deburring force. Implementation of and experiments with the proposed strategies are described.

Key Words. Deburring; force control; grinding; machining; position control; robots; teaching

1. INTRODUCTION

Deburring has been proved to be a hard task for industrial robots. For a successful deburring the robot should be able to sense positional inaccuracies and burr variations and take corresponding actions based on the sensed results. Most of the deburring strategies proposed in the literature (Bone and Elbestawi, 1989; Dornfield and Erickson, 1989; Haefner *et al.*, 1986; Kazerooni, 1987; Liu, 1992a; Plank and Hirzinger, 1982; Puls and Barash, 1985; Stepien *et al.*, 1987) worked in a *passive* way because the burr variations were detected during the deburring procedure. Problems with a *passive* deburring strategy are twofold: (1) a burr could be only recognized with a time delay after a change of some sensor information (e.g., force, acoustic signal, current, power, *et al.*) was detected; and (2) special efforts should be made to distinguish burr variations from positional inaccuracies because both of them could result in similar changes of the sensor information. To solve these two problems Liu (1992b) proposed recently an *active* deburring strategy by detecting the burr variations through edge following in advance. In this paper the *active* deburring strategy is improved in the following two aspects: (1) the contact between the tool and workpiece is generalized from point contact to line contact so that it is applicable to burrs located on workpiece surfaces instead of only those along workpiece edges; and (2) the burr detection strategy is extended to deal with various positional inaccuracies and application-related requirements.

2. AUTOMATED MOTION GENERATION

Suppose there are a series of workpieces to be deburred shown in Fig. 1(a). There are burrs on the surface between A and B, but the burr sizes and locations are unknown. To enable an industrial robot to remove the burrs the following three things should be done: (1) the desired robot motion should be determined; (2) the unknown burrs should be detected; and (3) a deburring strategy should be developed. This section deals with the automated motion generation through contour following.

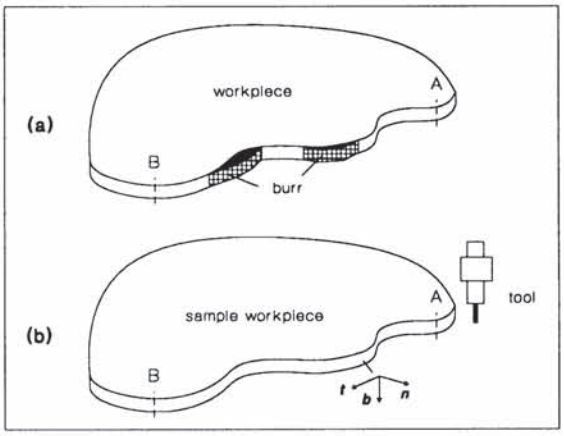

Fig. 1. Workpiece Contours

Assume that there exists a sample workpiece shown in Fig. 1(b). Through *teach-in* method a set of support positions of the workpiece surface can be obtained: $\mathbf{x}_1, \mathbf{x}_2, \cdots, \mathbf{x}_n$, where $\mathbf{x}$ is given by $\mathbf{x} = [p_x \; p_y \; p_z \; \theta_x \; \theta_y \; \theta_z]^T$. These support positions provide rough information about the workpiece contour. For the workpiece shown in Fig. 1 only the starting and end positions (A and B) are required while for a more complicated workpiece more intermediate positions are needed.

Basic requirements for a successful surface following are the abilities to control the contact force between the tool and workpiece in the normal direction and to control the tool motion along the tangential direction

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of the workpiece contour. Because the workpiece contour between the support positions is unknown the robot motion cannot be globally determined in advance. At every position along the workpiece surface the tangential and normal directions (**t** and **n**) are to be identified so that in the tangential direction a local movement can be specified and in the normal direction the contact force can be controlled.

The initial tangential direction can be determined approximately by the first two support positions $\mathbf{x}_1$ and $\mathbf{x}_2$ (in the example, positions A and B):

$$\mathbf{t}_0 = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}_{\mathbf{x}_2} - \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix}_{\mathbf{x}_1} \qquad \mathbf{t} = \mathbf{t}_0/|\mathbf{t}_0| \quad (1)$$

After the robot starts to move the tool center point changes. The history of the tool center point can then be used to find the tangential direction. Let the tool center point at the kth sampling time be denoted by vector $\mathbf{p}(k)$. Then the actual tangential direction of the surface can be calculated by:

$$\mathbf{t} = [\mathbf{p}(k) - \mathbf{p}(k-i)]/|\mathbf{p}(k) - \mathbf{p}(k-i)| \quad (2)$$

where i is an integer number. Experiments suggests that i can be taken as 1, 4, or 8, depending on how fast the tool moves. For fast movements i is taken as 1, which means that the tangential vector is determined from the last and actual tool center points, while for slow movements i is taken as 4 or 8. An interpolation algorithm could be considered in place of eqn. (2). However, experiments have shown that eqn. (2) gave satisfactory results already.

Because the normal direction is perpendicular to the tangential direction and the tool axial direction ($\mathbf{z}_{tl}$, determined by the robot position) it can be calculated by:

$$\mathbf{n} = [\mathbf{t} \times \mathbf{z}_{tl}]/|\mathbf{t} \times \mathbf{z}_{tl}| \quad (3)$$

and finally the binormal direction is given by:

$$\mathbf{b} = \mathbf{n} \times \mathbf{t} \quad (4)$$

The three unit vectors **n**, **t** and **b** build the three axes of the constraint coordinate system $\{C\}$, in which feedback controls are performed. To implement force control on a position-controlled robot controller the *corrective position/force control* approach proposed by Liu (1992a,b) is utilized. In the normal direction a motion correction is generated by controlling the contact force: $\delta_n = g_1(f_d - f)$, where f_d and f are respectively the desired and actual contact force between the tool and workpiece, and $g_1(\cdot)$ represents the force controller. In the tangential direction the tool velocity is controlled, so a motion correction is given in the tangential direction by: $\delta_t = \int g_2(v_d - v)\,dt$, where v_d and v are respectively the desired and actual tool velocity, and $g_2(\cdot)$ represents the velocity controller.

With the normal force control the tool gives a constant press force on the surface. As the tool travels from one support position to another it follows the unknown workpiece surface. The robot trajectory is recorded during the surface following and based on the recorded trajectory the unknown workpiece surface can be identified and the desired robot trajectory for deburring can be determined. To increase the positional accuracy the surface following procedure may be repeated. In this case the robot trajectory obtained in the previous procedure is used as the desired trajectory for the next procedure.

3. BURR DETECTION

In this section the strategy of surface following is extended to detect unknown burr sizes. The reason why a simple force/torque sensor is used for burr detection instead of an expensive video camera system is that a force/torque sensor is needed in the deburring procedure anyway and the background in a deburring cell is too dirty for a video camera. In addition there are some features of a workpiece that are easy to grasp by human persons but difficult for a video camera system, so one can take the advantage of these features in burr detection by building a fuzzy man-machine-interface.

Through the contour following of a sample workpiece, as discussed in the previous section, the desired robot trajectory is obtained. The workpiece to be deburred is then followed with the help of this desired trajectory to get the burr sizes. At this time the normal, tangential and binormal directions of the workpiece contour are known in advance. In presence of burrs the robot motion is adjusted in the normal direction under the normal force control. The desired and actual constraint coordinate systems are shown in Fig. 2(a), in which **n**-**t**-**b** is the desired and **n**′-**t**′-**b**′ the actual constraint coordinate system. The displacement between the two systems h reflects the height of the burr, which may vary along the workpiece surface. Fig. 2(b) shows an example of the displacement along a whole workpiece surface. Under ideal conditions, that is, there are no workpiece tolerances, no positioning errors, and no tool wear, this displacement describes exactly the burr height. In general cases it involves positional inaccuracies, which must be compensated.

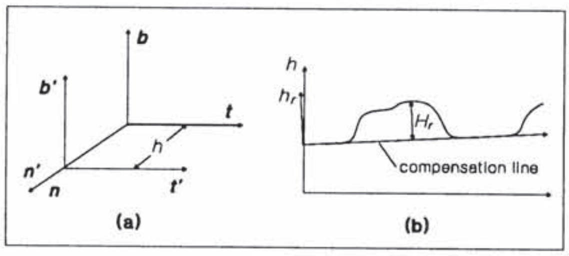

Fig. 2. Trajectory Displacement in Burr Detection

To get the burr height a *compensation line*, a *relative burr variation* and a *degree of burr variation* are introduced. The *compensation line* is defined as the straight line closest to the trajectory displacement from below (Fig. 2(b)) and the *relative burr variation* is defined as the difference between the trajectory displacement and the compensation line, as shown in Fig. 2(b) by h_r. The trajectory displacement is divided by the compensation line into two parts, the lower part of which contains generally positional inaccuracies. If the compensation line is not horizontal orientation inaccuracies of the workpiece are then detected. The *degree of burr variation* ρ is defined by:

$$\rho = (H_{max} - H_{min})/H_{max} \quad (5)$$

where H_{min} and H_{max} are respectively the smallest and biggest burr height to be determined. With the help of the relative burr variation ρ can be rewritten as: $\rho = H_r/H_{max}$, where H_r is the maximum relative burr variation (see Fig. 2(b)).

For many applications burrs are located only on some part of the workpiece, as shown in Fig. 3(a). The burr height can then be given directly by $h_b = h_r$. In this case we have $\rho = 1$. For some applications burrs exist everywhere along the workpiece contour as shown in Fig. 3(b); in this case the relative burr variation given by h_r is only one part of the burr, the other part is constant along the whole workpiece contour and cannot be identified from the trajectory displacement because of positional inaccuracies. For some other applications (e.g. for *chamfering*) not only burrs but also a layer of material along the whole contour should be removed; again a variable and a constant part of the contour should be removed. For the latter two types of applications we have $\rho < 1$.

To deal with these applications the following restriction is made: it is assumed that only the final shape of the contour is of importance while the workpiece size allows some tolerances so that the depth the tool cuts into the workpiece is not required to be very accurate. This restriction makes it possible that the burr size is determined approximately with the help of a fuzzy man-machine-interface. First the biggest burr height is calculated by $H_{max} = H_r/\rho$, where the degree of burr variation ρ is specified by the operator through the fuzzy interface, with values like *one, very big, big, small, et al.* with *one* corresponding to the special case that burrs exist only on some parts of the workpiece contour (Fig. 3(a)). The actual burr height can then be determined by $h_b = h_r + [H_{max} - H_r]$.

The cross-sectional area of a burr is calculated based on its height and form: $\sigma = \sigma(h_b)$. For those burrs shown in Fig. 1(a) the burr size remain constant in the binormal direction **b**, so σ is calculated by: $\sigma = wh_b$, where w is the burr width. In many cases the cross-section of a burr takes the form of a triangle approximately and the base of the burr triangle is proportional to the burr height, so σ is calculated by: $\sigma = \kappa h_b^2$, where κ is the proportional coefficient. Various burr forms can be specified by the operator also through the fuzzy man-machine-interface.

4. DEBURRING STRATEGY

Based on the contour following strategies developed in the previous two sections an *active* deburring strategy is proposed in this section, which can be characterized as a *three-step* deburring strategy. The first step is the contour following of a sample workpiece to automatically generate the desired trajectory of the robot manipulator. The second step is the contour following of the workpiece to be deburred to get the variation of the burr size based on the trajectory difference between the sample workpiece and the workpiece to be deburred. The third step is the deburring procedure itself, during which the robot is moved along the desired trajectory determined in the first step and at the same time the cutting force is controlled according to the burr sizes detected in the second step.

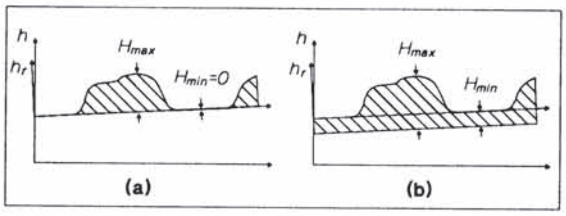

Fig. 3. Burr Size Variations

There are two main differences between the deburring procedure and contour following procedures. The first difference is that the tool motor is turned off for contour following and turned on for deburring for material removal. The second difference is that in case of deburring the desired cutting force is specified as a function of the burr sizes detected. As discussed by Liu (1992a) the static model of the deburring process can be expressed by a nonlinear function: $f = \phi_{db}(\sigma, v)$, where f is the cutting force, σ is the cutting cross-sectional area, and v is the tool speed. According to the cross-sectional area detected the desired deburring force is determined by: $f_d = \phi_{db}[\sigma(h_b), v_0] = \hat{\phi}_{db}(h_b)$, where v_0 is the specified constant tool speed for deburring.

5. IMPLEMENTATION AND EXPERIMENTS

The experimental system used for contour following and deburring is composed of a robot manipulator, a robot control unit, a control computer, a force/torque sensor, and an air-motor-driven deburring tool of cylindric type. The 6-DOF joint manipulator Manutec r3 is controlled by a Siemens robot control unit RCM 3. Through an ISRA-PRCI (PC Robot Control Interface) the RCM 3 is connected to the control computer. It receives motion corrections from the control computer and coordinates the motion corrections with its planned path. The 6-DOF DFVLR force/torque sensor, mounted between the robot hand and the deburring tool, works at the principle of strain gauge.

The control computer is an IBM AT with processors 80386/80387. It acquires the sensed forces/torques and robot positions, performs the position/force control, and transmits the motion corrections to the RCM control unit. Contour following and deburring algorithms are realized on the control computer in *Microsoft C* with a sampling period of 8 ms. Functions, like sensor and task-related configurations, contour following and deburring strategies, and graphics and DOS functions, are all managed under top-down menus. To get a series of support positions, like A and B in Fig. 1, the robot is moved to the desired positions under force supervision and per request the current robot position data are transfered to the computer. After the contour following of a sample workpiece the recorded robot trajectory data are compressed and transfered back the RCM to serve as the desired trajectory for burr detection and deburring. After the contour following of the workpiece to be deburred the burr variations are detected and the desired robot motion on the computer is extended to include a trajectory of the desired deburring force. After the deburring procedure the actual robot motion is compared with the desired one and if necessary the deburring procedure can be repeated. During any contour following or deburring procedure data exchanges between the RCM and the computer are performed automatically every sampling period: actual robot position to the computer and motion corrections and supervision signals to the RCM. All recorded data can be displayed in graphics after a procedure is finished.

Experiments for surface following and deburring were conducted on plastic and aluminium workpieces under various conditions. It has been shown that with the proposed three-step deburring strategy the robot could deburr successfully in presence of positional inaccuracies and burr size variations. The experimental results presented here were conducted on a plastic workpiece with a desired linear contour. The workpiece contour before and after the deburring procedure is shown in Fig. 4. It can be seen that the burr was successfully removed. In the burr detection the degree of burr variation ρ was specified in this example as *big*. Through experiments with similar burrs it was found that different values of ρ led actually only to different cutting depthes into the workpiece but in all cases the variable part of the burr could be removed. This result is useful for chamfering, where the depth of the chamfer can be specified by the degree of burr variation. The actual deburring force is shown in Fig. 5. By comparing Fig. 4 and 5 it can be found that the deburring force took actually a similar form to that of the workpiece contour before deburring.

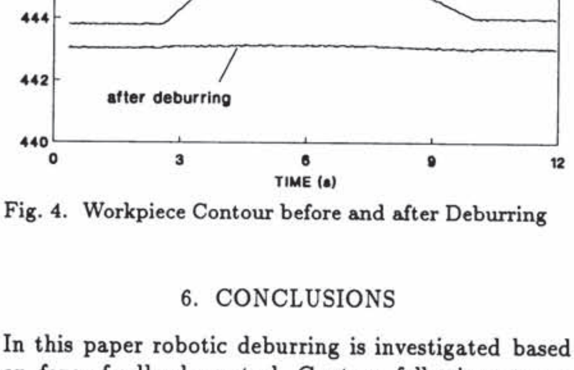

Fig. 4. Workpiece Contour before and after Deburring

6. CONCLUSIONS

In this paper robotic deburring is investigated based on force feedback control. Contour following strategies for automated motion generation and for burr detection are proposed. A three-step *active* deburring strategy is developed, under which the robot is moved along the desired trajectory identified and at the same time the cutting force is controlled according to the variation of the burr size detected. The contour following provides an automated way to generate the robot motion for deburring tasks and an easy but efficient way to detect unknown burr sizes and locations. The three steps of the *active* deburring strategy utilize the same sensor system, which makes the whole system united and compact. Our present work is to improve the three-step deburring strategy by a knowledge-based system.

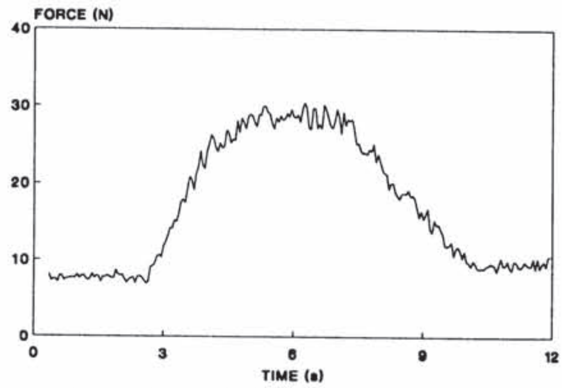

Fig. 5. Cutting Force during Deburring

7. ACKNOWLEDGEMENT

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