AN ADVANCED DEBURRING AND CHAMFERING SYSTEM

KARL N. MURPHY and FREDERICK M. PROCTOR
Robot Systems Division
National Institute of Standards and Technology

ABSTRACT

A second-generation automated deburring cell is currently under development at the National Institute of Standards and Technology. This cell will be capable of automatically generating, from part geometry and machining information, a series of robot paths for deburring aerospace parts made from superalloys. In order to compensate for the inaccuracy of robots when following computed coordinates, an actively-controlled end effector will be used to precisely position a rotary file in response to forces sensed at the part edge.

INTRODUCTION

Research has been underway at the National Institute of Standards and Technology since 1983 on methods to automate the deburring of machined metal parts. The goal of this research is a fully automated deburring cell capable of processing parts based only on their geometry and machining history, with no human intervention.

Such a deburring cell must contain several key elements: a process planner, which determines the sequence of events to take place; a trajectory planner, which computes actual deburring trajectories; a workcell controller, which schedules activities in the cell; and one or more robots to position the parts and perform the deburring [1]. Comprehensive computer-aided design (CAD) models are assumed to exist which define the part geometry and the machining operations completed prior to deburring.

The process planner can be effectively implemented as an expert system which encapsulates the knowledge of a human. The role of the process planner is twofold. First, it must determine the likely nature and location of burrs based on the part geometry and machining history. Second, it must consult models of burr removal to determine which deburring processes will effectively remove the burrs.

The trajectory planner uses the sequence of part features and the processes to be applied to these features to develop a set of robot trajectories that will accomplish the deburring. These trajectories consist of coordinates corresponding to the part features to be deburred, augmented with housekeeping data such as tool commands, approach points, and depart points.

This work is partially funded by the U. S. Navy Manufacturing Technology Program. Equipment listings are given for clarity and do not imply a recommendation by NIST.

Unfortunately, the use of computed coordinates places stringent requirements on the robot's accuracy (the ability of the robot to move to a specified point in space) rather than its repeatability (the ability of the robot to return to a previously recorded position). This is a major problem, since the accuracy of commercial robots is often several orders of magnitude worse than the repeatability. Many programmers do not know the poor accuracy of their robots, mainly because most robots are taught by showing, a method that does not require high robot accuracy.

Several methods can be used to accommodate for inaccuracy: calibration, sensory feedback, and the selection of a forgiving process. Calibration methods include kinematic model calibration where parameters that define the link lengths and joint offsets are precisely measured for a particular robot. Another calibration methods is error mapping where the robot's errors are tabulated in various regions of interest. Unfortunately, calibration does not account for dynamic loading, deformation, or external uncertainties such as part misplacement, errors in machining, or part tolerances. The use of sensory feedback can reduce these external uncertainties, but often the robot controller's large time delays and joint friction render closed-loop control of the robot end-effector unsatisfactory. Therefore, it is important to select a deburring process which is sufficiently forgiving to accommodate the remaining inaccuracies. This can be accomplished with passive compliance, or an actively-controlled end effector.

A typical scenario of a fully-automated deburring cell would be as follows: a CAD description of a part is developed, which at deburr time contains a complete machining history as well as any specific deburring requirements. Next, the expert system process planner consults models of burr formation and the CAD model to determine probable burr types and locations. The process planner then associates tools and tool parameters with these burrs by consulting models of burr removal. The trajectory planner computes the sequence of robot paths required to acquire, fixture, and deburr the part based on the edges, tools, and parameters selected. To ensure satisfactory deburring, real-time sensory feedback and end effector compliance account for robot inaccuracy. The workcell controller supervises the overall process, scheduling cell tasks and communicating with the higher levels of the factory.

Researchers at NIST have been developing workcells which approach the ideal of full automation. The Cleaning and Deburring Workstation (CDWS), begun in 1985, demonstrates the feasibility of deburring soft metals based on a graphicall developed process plan and robot trajectories computed automatically from CAD data. A next-generation workcell capable of processing high-strength aerospace superalloys using an actively-compliant end effector is currently under development. This workcell, the Advanced Deburring and Chamfering System, will demonstrate the same off-line programming benefits shown by the CDWS, while furthering its capabilities.

THE CLEANING AND DEBURRING WORKSTATION

A first-generation automated deburring cell, the Cleaning and Deburring Workstation, began as part of the Automated Manufacturing Research Facility. Research in the CDWS encompasses hierarchical real-time robot control, task scheduling, and off-line programming. Information on various aspects of the CDWS can be found in References [2, 3, 4].

The CDWS consists of a workstation controller, two robots, various quick-change deburring tools, a rotary vise for part fixturing, a buffing wheel system, and a part washer and dryer. The workstation controller is a set of software modules which perform process planning and task scheduling. A Unimate 2000 six-axis hydraulic robot performs part handling and buffing. A PUMA 760 six-axis electric robot, fitted with a quick-change wrist, selects end-effectors from a tool rack containing a rotary end brush, a countersink tool, a hole brush, and a gripper. The vise can be rotated, reducing robot motion required for part refixturing and deburring.

Ahuman expert develops the process plan at a graphics terminal displaying CAD images of a part. Using a mouse pointing device, the user selects features to be deburred, and associates tools and tool parameters to each feature. Part handling information is similarly generated. Once this process plan is developed, a trajectory planner computes robot coordinates necessary to handle the part and to deburr the specified features.

Various methods are used to accommodate for robot inaccuracy. Error mapping reduces part handling error to an extent that can be tolerated by the fixturing devices. For deburring, a two-pass technique known as self-teaching is used. On the first pass, the robot approaches the computed points, moves toward the part edge until a desired force is met, and updates each computed point with the current position. On the second pass, the robot deburrs the part, using this new set of points.

While this system demonstrates a substantial savings in time when compared with teach programming, it is not fully automated. A human expert is still required to select the edges, tools, tool parameters, and part handling data. Furthermore, only soft metals such as aluminum and brass can be deburred since deburring harder metals require non-compliant cutters. When used with the CDWS robot, hard cutters generate chatter, a scalloped edge. The use of hard cutters in an improved system is being jointly developed by NIST and industry under the sponsorship of the U.S. Navy's MANTECH program, as part of a solution for the automated deburring of aerospace parts.

THE ADVANCED DEBURRING AND CHAMFERING SYSTEM

The Advanced Deburring and Chamfering System (ADACS) incorporates CAD-based programming automation, with the addition of active hard-tooling to compensate for robot errors. Robot programs are developed automatically from CAD part data, and downloaded to a Cincinnati Milacron T3 robot at run time. The end effector, a TriKinetics Adaptive Deburring Tool (ADT), consists of a high-speed spindle and rotary file mounted in an active housing, which is gimbaled to provide two degrees of freedom. Sensors monitor the deburring forces and the position of the tool tip relative to its center location. Two independent force control laws allow for compliance to be varied in the normal and tangential directions. In addition, the orientation of the tool's normal vector can be specified continuously, allowing it to be changed quickly while following complicated edges and sharp corners. The addition of this active end effector results in two distinct yet coupled control problems: a macromanipulator which executes gross motion at relatively low frequency, and a micromanipulator which executes fine motion at a much higher frequency. Ablock diagram of the ADACS is shown in Figure 1.

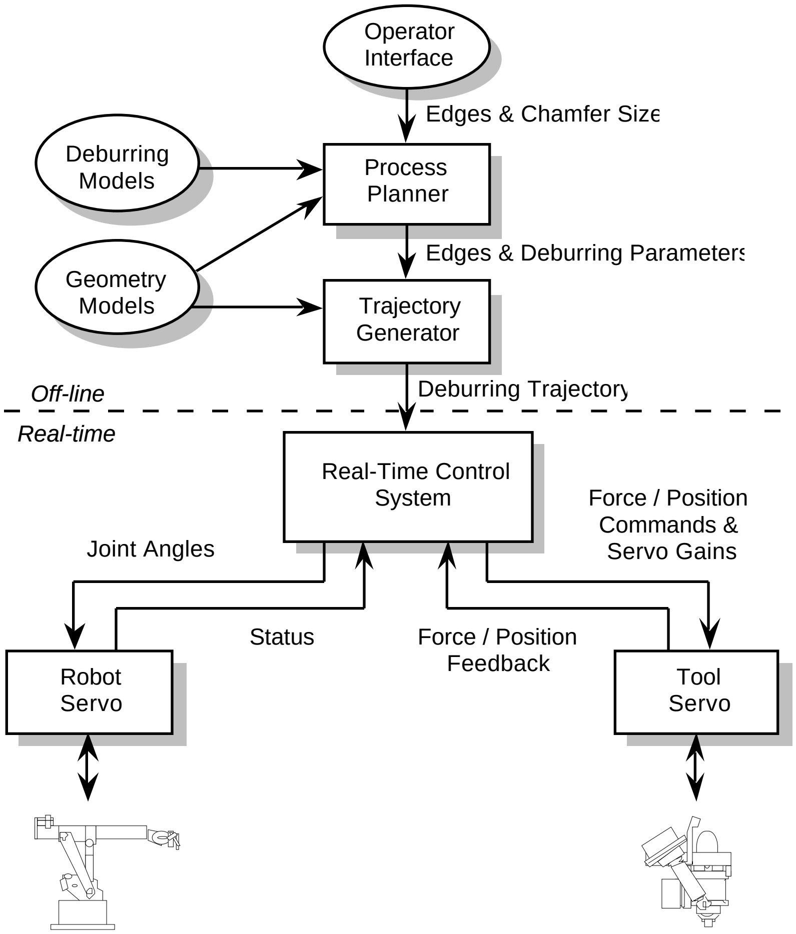

Figure 1. The Advanced Deburring and Chamfering System. A user selects edges and chamfer sizes. A process planner consults deburring models to determine how the part should be deburred. A trajectory generator computes deburring paths, which are sent to the real-time control system for division into robot and tool tasks.

Tooling

Hard cutters require compliant tool holders, either passive or active, which perform two main functions: reducing chatter and keeping the tool on the part despite robot and system inaccuracies. In contrast to machine tools, whose structural stiffness is high in all directions, the relatively low stiffness of robot arms allow large-amplitude resonances which cause chatter. Asada and Goldfine [5] have analyzed the mechanics of robotic grinding, and shown that chatter is reduced when the normal and tangential stiffnesses differ by a factor of ten, as shown in Figure 2. This difference in relative magnitudes and direction of stiffness reduces the otherwise strong coupling between the normal and tangential directions. Since the overall stiffness depends on both the tool and the robot, a tool must have an axis with stiffness less than a tenth of the stiffness of the robot.

Robot accuracy is not sufficient for edge following when deburring machined edges with hard cutters. In this case, the normal direction must be made compliant, so that the cutter will remain in contact with the edge and sustain the small normal forces needed for edge breaking. Often, the burr variation is small enough so that the depth of cut is unaffected.

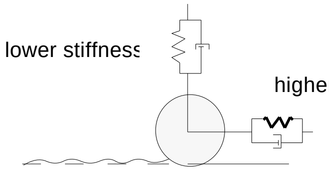

Figure 2. The 10:1 Rule. To reduce chatter, normal and tangential stiffness of the tool holder should differ by an order of magnitude or more. When deburring machined edges, the tangential stiffness is often chosen higher, as shown.

Compliance can be implemented either passively or actively. The ADT, shown in Figure 3, is an actively compliant tool which has several advantages over a passive tool holder. The compliance and desired force in both the normal and tangential directions are inputs to the tool controller and, therefore, can be easily changed for different materials, burr conditions, or desired chamfer size. Furthermore, a robot would have to physically rotate a passive tool holder to change the normal axis orientation. In contrast, the axis orientation of the ADT is determined electronically and can be rotated at high speeds. This allows for following complex edges without slowing the feed rate during tool rotation. The control of the ADT is described by Hollowell [6].

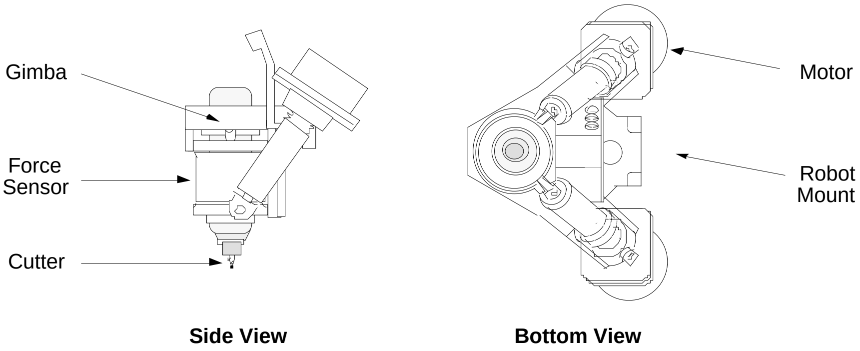

Figure 3. The Adaptive Deburring Tool. The tool consists of a high-speed spindle and rotary file mounted in a two degree-of- freedom motorized housing

Real-Time Control System

Considerable work on hierarchical real-time control systems has been carried out at NIST over many years. The NIST Real-time Control System (RCS) is being demonstrated on many platforms including the CDWS robot controller, the robot controller in an automated horizontal machining workstation, the mobility controller for teleoperated military vehicles, and the control system for the NASA Flight Telerobotic Servicer [3, 7, 8].

RCS is a hierarchy of three sets of computing modules: task decomposition, world modeling, and sensor processing. The task decomposition modules perform real-time planning, control, and monitoring functions. They decompose task goals both spatially and temporally. The sensory processing modules detect, filter, and correlate sensory information. The world modeling modules estimate the state of the external world and makes predictions and evaluations based on these estimates.

The ADACS RCS (See Figure 1.) decomposes deburring trajectories into commands for the robot and tool controllers. Although the robot servo control law is supplied by the vendor and is inaccessible at the lowest levels, provision has been made to allow for joint positions to be specified at a rate of 65 Hz. Similarly, the tool control laws are inaccessible, but the values for stiffness, damping, force setpoints, and axis orientation can be modified at a rate of 120 Hz.

There are two classes of robot and tool synchronization problems encountered in the ADACS. First, there is the problem of coordinating commands to the robot and tool controllers during the traversing of complicated geometries. RCS must rotate the tool normal vector as the tool traverses corners. Second, there is the problem of accommodating tool-tip straying. Since the tool controller maintains cutter contact with the edge, the tool-tip will stray from the center of its actuation range when the error in the robot's trajectory increases. RCS must correct the computed trajectory in the robot controller when the tool strays too far.

SUMMARY

A second-generation automated deburring system capable of processing aerospace materials is currently being developed at the National Institute of Standards and Technology. This system consists of an off-line programming interface which allows complex deburring trajectories to be developed from CAD data without the need for robot teach programming. These trajectories are downloaded to a real-time controller, which coordinates the motions of a position-controlled robot with an actively-compliant deburring tool. The tool can be commanded to maintain contact with a part edge with a prescribed force, so that robot and part inaccuracies are accommodated in real time.

REFERENCES

1. F.M. Proctor and K.N. Murphy, "Advanced Deburring System Technology," ASME Winter Annual Meeting, PED 38, San Francisco, CA, (December 10-15, 1989).

2. F.M. Proctor, K.N. Murphy, and R.J. Norcross, "Automating Robot Programming in the Cleaning and Deburring Workstation of the AMRF," Proceedings of the SME Deburring and Surface Conditioning, San Diego, CA, (February 1989).

3. K.N. Murphy, R.J. Norcross and F.M. Proctor, "CAD Directed Robotic Deburring," Second International Symposium on Robotics and Manufacturing Research, Education, and Applications, Albuquerque, NM, (November 1988).

4 R.J. Norcross, "A Control Structure for Multi-Tasking Workstations," Proceedings of the IEEE Conference on Robotics and Automation, Philadelphia, PA, (April 1988).

5. H. Asada and N. Goldfine, "Optimal Compliance Design for Grinding Robot Tool Holders," IEEE Conference on Robotics and Automation, St. Louis, MO, (March 1985).

6. R. Hollowell, "Hybrid Force/Position Control for Robotic Light Machining," Robotics and Remote Systems Conference, Charleston, SC, (March 1989).

7. S. Szabo, H.A. Scott, and R.D. Kilmer, "Control System Architecture for the TEAM Program," Second International Symposium on Robotics and Manufacturing Research, Education, and Applications, Albuquerque, NM, (November 1988).

8. R. Lumia and J. Albus, “Teleoperation and Autonomy for Space Robotics,” Robotics 4(1), 27-33 (March 1988).

Presented at: Third International Symposium on Robotics and Manufacturing, British Columbia, Canada, July 1990.