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The Robotic Edge Finishing Laboratory

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Abstract

The Robotic Edge Finishing Laboratory at Sandia National Laboratories is developing four areas of technology required for automated deburring, chamfering, and blending of machined edges: (1) the automatic programming of robot trajectories and deburring processes using information derived from a CAD database, (2) the use of machine vision for locating the workpiece coupled with force control to ensure proper tool contact, (3) robotic deburring, blending, and machining of precision chamfered edges, and (4) in-process automated inspection of the formed edge. The Laboratory, its components, integration, and results from edge finishing experiments to date are described here. Also included is a discussion of the issues regarding implementation of the technology in a production environment.

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1 Introduction

Burrs are caused by many machining processes including drilling, milling, turning, and broaching. Edge finishing (deburring, chamfering, and blending) during manufacturing is important for three main reasons: (1) sharp edges pose a personnel hazard since they can cause injuries, (2) part mating may be more difficult due to clearance restrictions caused by burrs, and (3) high stress concentrations at sharp corners can cause product failure.

In batch production environments, edge finishing is typically performed manually using two methods: (1) hand held power tools with brushes, abrasive tips, or rotary files and (2) manual files and knives. The techniques employed with these tools are not well documented and inspection of deburred edges is not quantitatively defined; typically the worker runs a finger over the edge to inspect his work.

Improving both the efficiency and quality of deburring is of major concern to manufacturers. Deburring is labor intensive and can represent a significant portion of the expense of manufacturing machined parts [6,12,16]. In addition, deburring is frequently a dirty, noisy, and undesirable job and a high turnover in personnel is the norm. Training personnel in proper deburring techniques is costly and this, coupled with the high turnover rate, adds to the overall expense of deburring [24]. Variations in the skill level of deburring personnel cause variations in the quality of the part. Errors encountered in the deburring operation which cause the part to be scrapped are costly as the part is near the end of its manufacturing cycle.

Many past attempts at automating edge finishing processes with robotics have not been successful. While some of the failures, particularly in the case of chamfering, occurred because the systems could not consistently perform the process within the required tolerances, many were based on poor economics. The expense of developing multiple fixtures for each part to be processed as well as the programming time required to teach the robot trajectories for the parts was prohibitive in the batch environments that were being addressed.¹

Researchers have been investigating robotic deburring as a means to alleviate the drawbacks of manual deburring. Lambrechts [14] developed and installed a robot system to deburr a variety of machined castings. Murphy, *et al.* [15,16], have designed a robotic deburring workcell that uses a computer model of the part and is integrated into a factory environment. Kazerooni, *et al.* [11,12], have implemented impedance control with a robot system so that the deburring tool is slowed down when large burrs are encountered. Shim and Kramer [19] have done research in tracking edges under force control. Kunkel [13] has set up a deburring workstation within a manufacturing environment. Vishnu, Cutkosky, and Erickson [21] described collision-free robot paths and the use of feedback control. In a related application, Edsall, *et al.* [5], have investigated the grinding of weld beads by using a robot and a

¹Mass finishing techniques such as tumbling and blasting are commonly employed when production quantities are large.

structured lighting system. Couture [2] has developed a robot-mounted, structured lighting system to inspect and quantify the dimensions of chamfered and rounded edges.

Commercially available robots are position controlled devices, i.e., the instructions to control the robot typically consist of commands to move to x, y, z coordinates. Robot programming is done by moving the robot to a desired position under manual control and recording that position in the robot's computer. Robot motion is generated by commanding the robot to return to some sequence of the previously taught locations; movement between taught locations is typically in a straight line. Therefore, using a robot to deburr a part frequently involves manually teaching the robot a large number of positions (often in the hundreds) to ensure that the taught robot trajectory accurately conforms to the part edge contour. Manually teaching a robot is an empirical, iterative, and tedious procedure [14]. In addition, taught robot trajectories have three disadvantages when applied to robotic edge finishing: (1) careful fixturing of the workpiece is required, which can be very expensive [7], (2) part design/manufacturing tolerances are not accounted for, and (3) tool wear is not accommodated, thus frequent tool replacement is required.

A research system for investigating robotic deburring and chamfering of machined edges has been developed at Sandia National Laboratories. The philosophy behind the project has been to use computer models to provide a description of the task to be done. The model is combined with sensory input so that the model does not have to be precise; the sensory input adapts the system to account for approximations (within limits). In the edge finishing system, the model is derived from a commercial CAD database and sensory input is provided by a vision system and real-time force control on the robot. In addition to the edge finishing process, a structured lighting system is being developed that will inspect the quality of the deburred edges. The entire system allows for greater system flexibility, reduced programming errors, increased process repeatability, reduced fixture costs, greater process speed, and superior quality assurance. Using this system, an aluminum test piece has been automatically brush deburred, and a precision chamfer of 0.012 ± 0.001 inch has been machined on this part. Also, a structured lighting system has been developed that automatically measures chamfer lengths and angles in 0.25 seconds.

The following section discusses the features needed in a robotic edge finishing cell. Section 3 describes the equipment and integration of the Robotic Edge Finishing Laboratory. Section 4 highlights the results to date in brushing, chamfering, and edge inspection. Conclusions and a description of the direction for our future work are included in Section 5. Finally, the issues involved in moving this technology from the lab into a production environment are raised in Section 6.

2 Requirements for Automated Edge Finishing

This section briefly summarizes the system requirements for a robotic edge finishing station. Typical deburring and chamfering operations, the use of a CAD database, part fixturing, robot requirements, and active compliance are discussed.

Two widely used edge finishing processes are brushing and cutting. Brushing is used when workpiece specifications require only the removal of burrs and do not call out a dimensioned edge break. Typical parts in this category include castings which require burr removal from the edges of machined features. Brushes of either steel or abrasive-impregnated nylon are commonly used (depending on workpiece material) when manually performing this operation. Brushing does not require high accuracy; the brush must contact the surface to be deburred, but precise contact force is not critical. Cutting involves forming a specified edge break; typically this edge break is either a radius or a 45° chamfer of a certain dimension. Design specifications generally require a closer tolerance on cutting operations than on brushing. Parts that require cutting include machined parts that must fit into other parts. Tools used in manual cutting include rotary files, reciprocating files, and knives.

The use of a CAD database offers an alternative to manually teaching a robot. The same CAD model used to design and manufacture a part can also be used to identify the edges which will require deburring.² The edge geometry data in the CAD description of the part can be used to automatically program the robot trajectories needed for edge finishing.

To obviate fixturing a part precisely, a vision system can be used to determine the location of the part. This world model of the part can be correlated to the CAD description by transforming the CAD geometry of the part to the robot's coordinate system. Errors may be introduced due to vision system inaccuracies which arise from digitization of the image, calibration errors, and algorithm errors.

Active compliance through the use of a force controlling servo loop is an important enhancement to a robotic deburring system. This greatly improves a robot's dexterity and allows it to perform tasks which would otherwise be impossible. Active compliance provides two benefits: (1) accumulated system errors (*e.g.*, vision system resolution, robot inaccuracy, tool wear, calibration errors, part tolerances, *etc.*) are accommodated by sensing and establishing the required tool contact forces and (2) desired tool contact forces are maintained by actively complying to changes in edge geometries as the robot is moving.

The considerations in selecting a robot include accuracy, number of axes, and payload. High accuracy reduces the errors in positioning the robot-held tooling. While a three or four axis robot is adequate to deburr planar parts, a five axis robot allows deburring of three dimensional parts (when using symmetrical tools).

²Burrs are produced where a cutter tooth exits the material and not where the tooth enters the material. Since the CAD system is used to define the tool paths (the CNC code) used to machine the part, it is generally possible to predict which machining steps will produce burrs and which direction they will extend from the edge.

Figure 1: Robotic Edge Finishing Laboratory (REFL)

Thus, the maneuverability associated with a greater number of axes allows both a broader range of workpiece geometries as well as reducing the number of tooling configurations required in the robot's inventory. The robot should have a rated payload of at least 5 pounds.

3 Robotic Edge Finishing Laboratory

The Robotic Edge Finishing Laboratory, shown in Figure 1, automatically deburrs or chamfers machined edges. The laboratory has been designed to research and demonstrate robotic edge finishing technologies and is comprised of sample workpieces, a robot system, process support components, a CAD program, a supervisory computer, a vision computer, and a structured lighting inspection system. The majority of the equipment in the REFL is commercially available and supported. The use of a particular piece of equipment does not necessarily constitute a recommendation of that equipment by Sandia National Laboratories. Alternatives are generally available.

Figure 2: Sample Workpiece

3.1 Sample Workpiece

The workpiece that the REFL is currently using to investigate robotic edge finishing is shown in Figure 2. This part, referred to as the crown, is similar to a part currently in production at the Department of Energy's Y-12 facility in Oak Ridge, Tennessee. The edge break requirements on all the teeth edges are specified to be 0.012 ± 0.004 inch, with either a chamfer or radius acceptable.

3.2 Robot System

The robot used in the REFL is an Adept One from Adept Technologies Inc. This arm was designed for vertical assembly tasks and has a SCARA configuration with five axes. The first two joints (shoulder and elbow) use direct drive technology, giving the joints higher precision and lower hysteresis than typically seen with gear driven joints. The last three joints are gear driven; joint three is a prismatic joint in the vertical direction, joint four is a rotation about the vertical joint three axis, and joint five is a rotation about a horizontal axis.

The Adept One is capable of fast motion, yet retains excellent repeatability. A simple test, using a configuration primarily dependent on joints 1 and 2, showed

a typical repeatability of ≈ 0.0005 inch. The accuracy of the calibrated robot is specified by Adept to be 0.003 inch (for a four axis Adept One).

The robot payload is restricted due to the addition of the fifth joint. The arm's original design did not include the fifth joint as this degree of freedom is typically unnecessary for vertical assembly tasks. The arm's maximum design payload is reduced from 13 to 5 pounds when the fifth joint is added due to the weight of joint five. The heaviest tooling currently in use in the REFL is just under 5 pounds, which is within specification. This tooling, described in Section 3.3.3, is a seven inch stack comprised of the force sensor, a quick change wrist, and a pneumatic grinder. With joint five at 0° (pointing straight down), the inertia of this tooling about joint four is well within specifications. When joint five rotates the tool stack about the horizontal axis, the effective inertia about joint four increases and the inertial load limit of joint four is exceeded at $\approx \pm 40^\circ$. Trying to move the arm with the inertial limit exceeded results in an undamped oscillation of joint four. Software is available from Adept that allows the joint four servo parameters to be changed in real time to prevent this instability. This, however, is achieved at the expense of joint four response time. The tooling, shown in Figure 3, was designed so that joint five never needed to be positioned beyond $\pm 25^\circ$ for the test piece in Figure 2.

The robot controller and operating system are based on V+ [20], a multitasking environment allowing one robot control task to be operated concurrently with several process control tasks. A robot control task is one that controls robot motion; a process control task can control peripheral equipment but cannot control robot motion. This capability is especially useful in the research environment of the REFL. For example, while the robot control program is controlling the robot motions, a process control task can be recording tool tip contact forces.

3.3 Process Support

Various process control components are described here. These include force control, force sensor, and tooling.

3.3.1 Force Control System

The Adept supplied force control system (FCS), shown in Figure 4, is a Cartesian kinematic system. Force and torque setpoints are specified along and about the axes of either the robot's world or tool coordinate frame. The force/torque servo error terms are realized as position errors in the same Cartesian frame. Three user-definable, diagonal matrices specify the parameters of the FCS. The selection matrix specifies which axes are to be both force and position controlled and which are to be just position controlled. The stiffness matrix sets the stiffness (the reciprocal of compliance) independently for each axis. Applied force/torque levels (which can be zero) are set with the bias matrix. All these parameters are axially independent,

Figure 3: Tooling Stack

allowing techniques such as guarded moves and guarded pushes to be used concurrently on different axes.³ All parameters and procedures of the FCS are accessed with V+ subroutine calls.

Two modes of force control are implemented in the REFL: force contact sensing and force servo controlling. The first mode uses force sensing to signal contact with the part; this is adequate for many brushing tasks. The second mode servo controls the tool contact forces in real time; this is used while cutting a chamfer on an edge. Both brushing and edge cutting are described in more detail in Section 4.

³A guarded move means to move to the desired position unless a force threshold is exceeded; a guarded push means to apply the desired force unless the boundary of a position envelope is crossed.

Figure 4: Force Control System

3.3.2 Force Sensor

The force sensor that supplies the FCS with force data is a six axis wrist sensor from JR³ Inc. [10]. This sensor is capable of amplification, filtering, and processing both force and torque. These force and torque levels are output through serial or analog ports. Force and torque envelopes can be specified for each axis; these envelopes define the range of values that are acceptable. Values outside of these envelopes trigger a signal that can be used to indicate contact. Two low pass filters, one analog and one digital, are available with user definable cutoff frequencies.

3.3.3 Tooling

The edge finishing capabilities required for the REFL necessitate that multiple tools be available to the robot. A quick change wrist, Applied Robotics XChange model Alpha [23], allows the robot to change tooling without human intervention. Two rotary tools have been used to date. The larger of the two is an ARO model 8479-1, which is a right angle grinder with a 0.25 inch collet and a free speed of 12,000 RPM. The second rotary tool is a Citex model 800 which is much smaller and lighter than the ARO grinder and consequently not as powerful. It has a 0.125 inch collet and 25,000 RPM free speed and is designed for smaller tooling.

A third tool, not yet evaluated, is an Engis FNL Di-Profiler reciprocating file. Various accessories, such as linear files, abrasive stones, and laps, can be used with

this tool. This tool will be evaluated for deburring or chamfering straight edges since a linear file is less susceptible to gouging than a rotary file.⁴ A potential problem with the Di-Profiler is that its weight, coupled with the force sensor and quick change wrist, will be over the 5 pound payload limit of the five axis Adept One.

3.4 CAD Program

Part edge geometries are extracted from the ANVIL-5000 CAD program written by Manufacturing and Consulting Services, Inc. [1]. This is accomplished by using an ANVIL-5000 utility to generate tool paths along the edges to be deburred. The tool paths are defined as a series of straight line segments; a segment consisting of beginning and ending tool center points with corresponding tool orientations. The tool paths are written to a file in APT code.⁵ This APT file is read by the supervisory program and parsed to extract the six values (X, Y, Z, and 3 direction cosines) describing each tool center point (leaving behind the CNC-related command syntax). The geometry is transformed to the robot coordinate system based on the world model generated by the vision system. The transformed geometry is sent to the robot controller which automatically generates the desired robot motion.

Note that a single straight line segment is used to define the geometry of an individual tooth edge, even though the individual edges of the sample crown workpiece are arcs. This approximation is compensated for by the active compliance provided with real-time force servo controlling.

3.5 Supervisory Computer

A hierarchical control structure utilizing message passing, as shown in Figure 5, is used to coordinate the activities of the REFL. At the top of the hierarchy is a Sun 3/160C Unix workstation serving as the supervisor, cell controller, and host to the CAD system. The supervisor sends commands to the robot controller, runs the CAD program, communicates with the vision system, and serves as the development environment for programming tasks.

Communications between the Sun and the robot controller are over a 19200 baud serial interface utilizing the DDCMP error-detecting protocol. The vision system communications are over an ethernet interface.

3.6 Vision Computer

The vision system used to determine part location is based on Datacube, Inc. [3] VME-based vision boards. These boards are controlled by a Heurikon HK68/V2FA

⁴This is because a linear file has a line contact with the part while a rotary file has a point contact.

⁵APT is a programming language designed to control CNC machining centers.

Figure 5: REFL Hierarchical Control Structure

68020 microcomputer [8] that is running the VxWorks real-time operating system from Wind River Systems [22]. Vision algorithms were implemented on this system in-house in C++, an object-oriented language similar to C. The test part is held in place by a general purpose three jaw chuck, so the orientation of the part is unknown. Knowledge of the part geometry is used to assist the vision system. In the case of the part shown in Figure 2, the hollow circular region is ignored during processing as this is where the three jaw chuck grasps the part. The vision algorithms look only for a notch in the side of the part. The orientation of the test part can be determined to within one half degree.

3.7 Inspection System

It is important to inspect a part after it has been chamfered to ensure that the part meets specifications. In typical production operations today, deburring personnel manually chamfer an edge and take a silicone casting of the edge. The casting is sectioned and checked on an optical comparator. If the edge break is not within specifications, the part is sent back to the work station. This time consuming process is iterated until the specifications are met. Of course, in the REFL, the goal is to cut the chamfer in a single pass. It then becomes necessary to measure the chamfer after it has been cut. While it is possible to measure the chamfer via the sectioning method, it is desirable to inspect the chamfer on-line and quickly.

Research into automatic inspection of edge geometries has been initiated in conjunction with personnel at Y-12 [2]. One approach employs an optical sensor based on structured lighting as shown in Figure 6. The equipment being used includes a

Figure 6: Structured Lighting Inspection System

Figure 7: Theory of Structured Lighting

Panasonic model WV-CD50 CCD camera (512X484 pixels) [18], a D. O. Industries model Zoom 6000 microscope lens [4], and a Newport model V-SLM-S2Z laser diode line projection system [17]. The lens has a Newport model V-LAS-780 bandpass filter to eliminate background illumination. The computing is done by a Heurikon HK68/V2FA 68020-based CPU [8] and Datacube vision processors [3], both operating in a VME bus.

The theory behind structured lighting is illustrated in Figure 7. Given a pixel in the camera, a vector from that pixel through the lens center can be constructed. In this case the vector equation is $P = F + \lambda c$, where P is a point along the line, F is the location of the camera, λ is a scalar unknown, and c is a known unit vector that is calculated from the illuminated pixel in the CCD array and the camera calibration matrix. The position of the laser is determined with calibration techniques so that the equation of the laser plane is known. In this case the plane

Figure 8: Force Corrected Brush Deburring

equation is $P \bullet u = R_0 \bullet u$, where P is a point in the plane, R_0 is a known point in the plane, and u is a unit vector normal to the plane. To reconstruct the true, three dimensional location of the point of interest, all that is necessary is to calculate the intersection of the vector with the plane. A particular advantage of this approach is that it is not necessary to calculate the absolute coordinates of an edge with respect to some coordinate system (*e.g.*, the robot's coordinate system). It is only necessary to compute a relative measurement with respect to the surfaces that compose the part edge. Thus, it is not necessary to precisely fixture the part. It may even be possible to use the chamfer measurement to servo control the chamfer tooling. Research issues include automatic calibration, focusing, and alignment of the edge within the camera's field of view.

4 Results

A laboratory for investigating robotic deburring and chamfering of machined edges has been developed. Initial experimentation has been performed on the test part shown in Figure 2. Robot trajectories are automatically generated as straight line segments for a specific part using information derived from a commercial CAD database (as described in Section 3.4). The use of vision and force sensing eliminates the need for precisely fixturing the parts and accurately defining the robot trajectories. Real-time force sensing ensures proper tool contact with the part during processing. The following sections describe the robotic brushing and chamfering operations in detail.

Figure 9: End Mill Cutting Tool with Guide

4.1 Brushing

Brushing is done with the ARO tool discussed in Section 3.3.3 and a 0.125 inch end brush. The time required to deburr all of the outside edges of the teeth of the crown is 5.5 minutes. This time includes determination of the part orientation, extraction of the edge geometries from the CAD database, automatic programming of the robot trajectories, and executing the actual brushing process.

To brush deburr the crown, the robot's tool transformation is located approximately one sixteenth inch beyond the tip of a new, unworn brush. This, as shown in Figure 8, ensures the tool is not in contact with the part when the robot is driven to the beginning point. (Recall that the robot trajectories consist of individual line segments with associated tool orientations at the beginning and ending points.) At the beginning point of the line segment, the robot moves forward along the tool axis until the force sensor, using a defined force envelope, indicates the required tool contact force has been established. The controller reacts to this flag and immediately stops the motion of the robot. The distance the tool tip moved from the beginning point to the contact point is automatically applied as an offset to the end point of the line segment, and the robot is driven to this resultant position. In this mode,

Figure 10: Uncut Edge and Chamfered Edge (10X)

positioning errors are sufficiently accounted for at the beginning and ending points of the edge. However, any variance of the edge between the beginning and ending points is accommodated only by the inherent compliance of the system (including brush, arm, and position servo loop stiffness).

4.2 Chamfering

Research into chamfering using a guided tool has been performed. A guide has been designed for use with an end mill which allows cutting only to a preset depth. This guide, housing a 0.125 inch end mill mounted on the Cratex tool, is shown in Figure 9. Note that the size of the chamfer is controlled by how far the end mill is recessed into the guide. Using this guide, chamfers of 0.012 ± 0.001 inch have been cut on the horizontal edges of the crown teeth. Since the guide is not symmetric

Figure 11: Guided Tool Compliant Axes

about the tool axis it can be set up to align with either the horizontal or vertical edges of the crown but not both at the same time.⁶ New symmetric tooling is being developed to overcome this problem. The top half of Figure 10 shows an uncut tooth of the crown and the bottom half shows a 0.012 inch chamfer cut well within the 0.004 inch tolerance along the top edge; this view is magnified 10 times.

When cutting a chamfer with the guided end mill, as shown in Figure 11, the tool transformation aligns the z axis along the axis of the end mill (normal to the edge), the y axis tangential to the edge, and the x axis across the edge. The robot is driven to the beginning position extracted from the CAD database of the part. As with brushing, the tool transformation ensures that the tool is approximately one sixteenth inch from the edge at this beginning position. The Adept Force Control System (FCS) is enabled and a positive bias force along the z axis causes the tool to be driven towards the edge. The guide must be carefully aligned for proper cutting, so a zero force is prescribed along the x axis to align the guide with the edge.⁷ When the desired normal contact force and guide alignment are established, the tool is driven along the edge to the end point. The FCS ensures the desired contact force is maintained throughout the path along the edge even though the tool path extracted from the CAD database is a straight line when, in reality, the part edge is an arc segment. The tool z axis is maintained normal to the edge (arc segment) throughout the path because of the commanded straight line motion. The end points of the line segment each specify a tool orientation which is normal to the edge at that point. During a straight line move between these two points,

⁶This is because the robot has only five axes.

⁷Any misalignment of the guide with the edge along the x axis results in a force along that axis due to the notch in the tool guide. Sensed forces along the x axis are used to align the guide while it is pressed onto the edge.

Figure 12: Contact Force During Chamfering Along Tool Axis

the robot controller synchronously reorients the tool from the orientation at the beginning point, to the orientation at the ending point. Thus, the Z axis of the tool is maintained normal to the edge at all times.

Figure 12 is a plot of the tool contact force along the z axis during chamfering of a single horizontal edge of the crown. The desired normal force in the z direction was set to 2 pounds. It can be seen by the graph that this desired force was maintained to within 0.3 pounds once contact was established. The initial 0.6 pounds fluctuation is a result of switching from searching for the edge (motion perpendicular to the edge) to moving along the edge (motion tangential to the edge). The robot approach velocity while establishing contact was 0.14 in/sec and the tool velocity tangential to the edge (feed rate) during chamfering was 0.19 in/sec. It is significant to note that the path derived from the CAD database was a straight line. The actual edge being chamfered is an arc with a length of 0.5 inch and a three inch radius. Thus, the force servo control was able to correct for model approximations without significant deviations from the desired normal force.

4.3 Inspection System

To date, a bench prototype system and a computing algorithm operating at 4 Hertz have been developed that automatically measure the length and angles of a chamfer, as described in Section 3.7.

To test the accuracy of the sensor, a coupon was made by cutting 11 chamfers of different sizes on a block of stainless steel. A total of four measurements were made of each chamfer with the structured lighting sensor, and the results were

Figure 13: Chamfer Geometry

averaged and compared with measurements made by technicians using an optical comparator. It should be noted here that there are four chamfer measurements to make to accurately describe the chamfer geometry. This is shown in Figure 13 as the two chamfer length measurements C_t and C_s , and the two chamfer angle measurements θ_t and θ_s . The technicians were not able to directly measure the chamfer angles, so for comparison purposes, the optical comparator data was used to calculate the chamfer angles.

Figures 14, 15, 16, and 17 show the results of a series of chamfer measurements. The first two figures are plots of the structured lighting measurement vs. the optical comparator measurement, thus perfect agreement between these two techniques

Figure 14: Top Chamfer Measurements

Figure 15: Side Chamfer Measurements

Figure 16: Difference Between Techniques for Top Chamfer Angle

Figure 17: Difference Between Techniques for Side Chamfer Angle

would result in the data points lying along the line as indicated. The angle measurements are plotted as the chamfer number (1-11) vs. the percent difference between the two techniques, thus perfect agreement would result in the data points lying along the line through zero as shown. These plots indicate excellent agreement with the optical comparator technique.

These results indicate that the structured lighting technique will be successful in measuring edge chamfers. This is particularly important in measuring chamfer angles, as there is no easy way to currently do this. Research will continue in this area with the goals being to place the inspection system on the robot and to speed up the edge measurement algorithm.

5 Conclusions and Future Work

The research performed in the Robotic Edge Finishing Laboratory has shown the feasibility of employing robotic systems for brush deburring and cutting high tolerance edge breaks without careful fixturing of the workpiece. Force servo control is capable of compensating for approximations made in modeling the workpiece as well as systematic errors such as position inaccuracies developed during part location using computer vision systems. Cutting tool guides, which prevent excessive material removal, provide smooth chamfers without gouging the edge.

Development of technology for unguided chamfering is a major research area in the REFL. Unguided chamfering is desirable as this would greatly reduce the number of special purpose tools needed to support generalized edge finishing operations. The primary research areas that have been identified based upon experimentation in the REFL are: sensor-based transition from noncontact to in-contact motion in a material removal operation, and control of tool motion tangential to the edge (feed rate).

The difficulty of transitioning from noncontact to in-contact motion is illustrated by the Adept FCS as currently configured in the REFL. Using the FCS, an average delay of 0.25 second is seen when transitioning between establishing contact with the edge (robot motion normal to the edge) and cutting the chamfer (robot motion tangential to the edge). Since metal is removed during this change in control modes, gouging of the edge can occur. Currently, gouging is prevented with the use of a guide. Research into development of sensing and high speed control strategies is required to perform the transition without excess material removal.

After controlled contact with the edge has been established, servo controlled robot movement along the edge is needed to cut a chamfer. Feed rate is a function of the material being cut, the tool used to do the cutting, as well as the cross sectional area of the cut. In deburring operations, the cross sectional area of the cut varies with burrs along the edge [11,12]. These changes in cross sectional area cause a variation in the tangential cutting force; a large cutting force could deflect the cutting tool. This deflection is not a problem for milling machines; their stiffness is

such that the tool would break before the machine is deflected. Robots, conversely, lack this large stiffness; consequently, the tool can be deflected from the edge by a large burr. To compensate, the feed rate must vary with the cutting area. In addition, the feed rate must be kept above some minimum threshold to prevent cutting too deeply into the part and producing an uneven edge. Research into the relationships among these factors is under way.

Preliminary efforts in unguided cutting have shown the system capable of cutting a chamfer with a ± 0.002 inch tolerance. This chamfer was cut along a vertical edge of a 304 SS coupon using a 20-flute, 0.25 inch diameter carbide burr rotating at approximately 21,500 RPM. A prescribed normal force of 0.5 pound with a feed rate of 0.75 in/sec produced a nominal edge break of 0.013 inch. While the surface finish of the cut was acceptable for many applications, it is anticipated that higher speed tooling will result in a smoother surface finish [9]. Consequently, 60,000 RPM tooling is being acquired in the REFL.

The robot's kinematic configuration used to feed the tool along the vertically-oriented edge is optimal in that the positioning and force servoing requirements decouple themselves to specific robot joints: the horizontal joints ensure the tool is pressed against the edge with 0.5 lb. force, the vertical joint feeds the tool along the edge, and the orientation (wrist) joints allow a small amount of passive compliance.

6 Technology Transfer to a Production Environment

The edge finishing system described in this report has demonstrated the feasibility of CAD-based robotic deburring. The system, comprising commercial hardware and in-house software, has proven to be quite reliable. The system has produced excellent results with guided-tool chamfering. Research into unguided chamfering is continuing.

In the laboratory this system is configured as a development and demonstration platform. Certain facets of its operation result from the desire to demonstrate the technologies associated with edge finishing. A production environment system including these technologies would differ from the REFL's system both in the allocation of hardware resources as well as operator interaction with and operation of the system.

6.1 Production System Hardware

Economics is the primary reason there will be differences between a development system and a production system. The required rate of return drives the hardware of a production system to have only those functionalities required to perform the specific task. On the other hand, the hardware resources committed to the REFL are selected to have, at a minimum, the capabilities required for the specific job, as well as more general features. An example of this is the use of the vision system in the

REFL. Vision sensors are general in that they are reconfigurable, through software, for different tasks. They are also expensive and require a controlled environment, but are justifiable if the number of tasks to be performed is large or is expected to grow. For more specific applications other means of part location (exclusive of individual fixtures), such as various forms of contact sensing, may be sufficient and much less costly.

A significant expense associated with the REFL is the use of an engineering workstation and the user license for ANVIL-5000. ANVIL-5000 was selected for use in the REFL on the basis of its widespread use at Sandia and within the DOE complex. It is anticipated that the majority of the production parts that would be addressed by an edge finishing system at Y-12 or Allied, Kansas City, would have been designed with ANVIL-5000. Consequently, the CAD information required for automatic robot trajectory generation could be accessed without the expense of another ANVIL-5000 user license as the edge finishing system could make use of the CAD model already in use at a particular site.

The workstation used in the REFL, a Sun 3/160, is the minimum Sun workstation capable of hosting ANVIL-5000. Without the need to access ANVIL-5000 at the production cell, a less powerful and less expensive computer could be selected for the supervisor. In fact, a Sun 3/50 was chosen for the REFL before it was learned that ANVIL-5000 required a more powerful computer.

The use of a workstation is also based on the hierarchical control structure. A separate workstation/supervisory computer promotes a structured development environment and aids in system error detection and correction. Once system development is done, however, subsequent implementation can retain a similar control structure in a reduced computing environment. Many commercial robot controllers are designed with process (or cell) control in mind. It would not be unreasonable to have the Adept controller serve as the cell controller (supervisory controller) in addition to its duties as the robot and ancillary equipment controller. Recall that the Adept controller hosts a multitasking environment, allowing all of the functions of the supervisory computer (short of ANVIL-5000) to reside within the robot controller, executing concurrently with the robot control tasks.

Implementing an edge finishing system without a separate supervisory computer and without the need for in-cell access to ANVIL-5000 would result in a system without the generality of the REFL's system, but a system well suited to a production environment. It also results in a system representing roughly 65% of the cost of that in the REFL.

6.2 Production System Operation

The primary operational difference between the REFL's system and a production implementation is the generation of robot trajectories for a given workpiece. For demonstration purposes in the REFL, the user is allowed (required) to select which edges he would like processed each time the system is operated. The intent here is to

show that the REFL's system is indeed extracting the required edge geometry from the CAD description of the workpiece. In production, this process would be done once per workpiece and the resulting geometric data stored for subsequent recall. To process a particular workpiece, the geometry data file would be recalled and processed through a coordinate transformation to account for the current location and orientation of the workpiece, and then sent to the robot controller.

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