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KEYNOTE ADDRESS: ADVANCED DEBURRING SYSTEM TECHNOLOGY

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ABSTRACT

Progress in manufacturing and material science has led to the need for improved deburring technology in three key areas: the measurement and modeling of burr formation and removal; the use of sensory feedback for intelligent tool and robot control; and the automation of process planning. This paper presents an automated deburring system paradigm, capable of processing parts based only on their computer-aided design descriptions, to underscore the research needed to provide these improvements.

INTRODUCTION

The development of new materials and the improvement of manufacturing techniques have resulted in the need for advanced deburring systems. This need is especially apparent in the aerospace industry, which is relying increasingly upon high-strength materials such as titanium and inconel for high-performance components. The hardness of these materials, and the requirements for precision deburring, have created difficulties that automated deburring systems are currently incapable of solving. Because of this, much deburring continues to be performed manually, in spite of the sometimes full automation of the rest of the manufacturing process.

While manual deburring is a workable solution, it has several limitations. It is tedious and time consuming. Continuing costs of wages and training due to turnover of trained personnel make manual deburring expensive. It has been estimated that the cost of manual deburring may reach 30% of the total part cost (Gillespie, 1987). Quality and output rate of deburred parts vary considerably as a result of complex psychological factors. Special precautions must be taken to ensure the safety of workers in a manual deburring cell.

In those cases where automation solutions can be found, they are typically so part-specific that changes in production may require a complete redesign of the deburring cell. This drawback, inflexibility, can be eliminated by the use of programmable equipment such as computer-numerical control (CNC) machines or industrial robots. CNC machines are attractive because of their stiffness and accuracy. However, the cost of these machines is often too great to warrant their use in a deburring cell, and many CNC machines cannot be used at all due to their intolerance of abrasive grit. Furthermore, CNC machine designers have limited the number of axes and range of motion in order to increase stiffness and accuracy, rendering these machines unfit for many applications.

Robots, in contrast, are less stiff and accurate, but offer larger work volumes and more controllable axes at less cost than CNC machines. They have been successfully incorporated in deburring cells, outperforming manual methods while providing a degree of flexibility unmatched by dedicated equipment. Although these robots usually rely on teach programming, a process by which a human operator steps the robot through the points it is to attain during deburring, research has been conducted to develop automatic programming methods (Proctor *et al*., 1989). These methods use computer-aided design (CAD) data and a representation of the robot's environment to compute robot coordinates offline, and rely on error compensation at runtime to correct for the inaccuracies of the robot.

To establish a context for this paper, it is helpful to consider an advanced deburring system paradigm. This system consists of two expert system modules, the *process planner* and the *trajectory planner*; a robot and robot controller; sensors, deburring tools, and tool controllers; fixturing devices; and a workcell controller. A diagram of this system is shown in figure 1. The system is capable of deburring any of a large class of parts, given only its definition. A typical scenario is as follows: a comprehensive description of a part is developed, which at deburr time contains a complete machining history as well as any specific deburring requirements. When the part arrives at the workcell, the expert system process planner consults models of burr formation and the 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 account for inaccuracy, sensory feedback is coupled with intelligent tool and robot control at runtime to ensure satisfactory deburring, given the computed trajectories. The workcell controller supervises the overall process, scheduling cell tasks and communicating with the higher levels of the factory.

Although this advanced deburring system does not exist today, it serves to illustrate the need for research in several key areas: measurement and modeling of burr formation and removal; integration of sensors for intelligent tool and robot control; and automation of process planning. The first three sections of this paper explain the requirements for each, survey the research efforts to date, and present perceived research needs. The final section describes examples of systems that approach the advanced deburring paradigm, and discusses their successes and shortcomings.

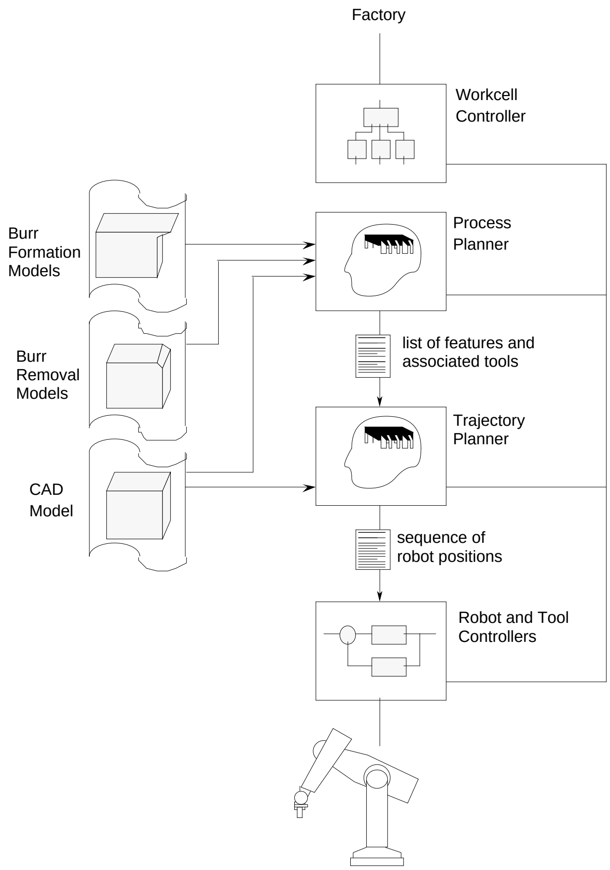


Figure 1. The Advanced Deburring System Paradigm. This system is fully automated, requiring no human intervention.

It is important to make the distinction between the removal of small burrs done during edge following (precision deburring) and the removal of large burrs such as cast flashing or weld beads (dimensioning). These processes represent the ends of a continuum, within which robotic deburring processes can be classified. In the former, the burrs are assumed to be small, so that chamfering or radiusing operations will be unaffected by variations in burr size. In the latter, edge following would result in a smoothing of the burrs, not their removal. For this, the tool must follow a prescribed path, slowing down for large burrs in order to remove them completely.

MODELING AND MEASUREMENT

At the lowest level of any automated deburring system lie the models upon which the automation strategies are based. For deburring, these models represent the effects of machining operations on the generation of burrs, and the effects of deburring operations on their removal. Their importance is manifold: tool design requires an accurate picture of deburring mechanics, and the proper choice of sensors depends on an understanding of signals generated by deburring.

At a higher level, these models are necessary to the process planner in determining burr type, location, and proper method of removal.

Modeling of Burr Formation and Removal

Although the expert system process planner in the advanced deburring system paradigm is local to the deburring cell, process planning will in general be distributed throughout an automated manufacturing facility. The reason for this distribution is manufacturability: in an automated manufacturing facility, parts are designed at a system, and a global process plan is developed at a high level for all the workcells in the factory. In many cases choices which appear arbitrary in the local process plans of one machining cell may have a profound effect on the operations which will be performed at a subsequent cell. For example, the choice of a milling direction may be inconsequential for a machining cell, but a poor location of the exit burr could complicate deburring. This manufacturability information must be developed before any machining operations occur, mandating the existence of some level of burr formation and removal models at the interface.

The process planning local to the deburring cell is more comprehensive than that done at the design stage, since more information is required to specify actual deburring processes than to determine the manufacturability described above. The responsibility of the deburring cell process planner is to generate a list of burr sizes, types, and locations for each part feature, and to associate deburring tools and tool parameters for their removal.

Burr formation models support the first function of the process planner: the generation of burr characteristics for part features, given the machining processes which formed the features. Empirical studies of burr formation have been undertaken for a variety of processes (Gillespie, 1981; Hickman, 1985). Other studies (Dornfeld and Ko, 1988) have quantified burr formation in terms of machining parameters, so that these models are useful in systems for which no empirical data is available.

The second function of the process planner is the selection of the proper tool and tool parameters for each burr or edge. Tool selection specifies cutter type such as brush or rotary file, and includes tool holder characteristics such as rigid mounting, passive or active compliance. Tool parameters include rotational speed, feed rate, and contact force. These models predict material removal rates and resulting edge quality given the size and shape of the burr, the type of metal, the type of the cutter, and the chosen tool parameters. The inverse formulations, or the selection of cutter type and parameters given burr characteristics, give rules which are consulted by the process planner when associating tools to edges.

As part of the tool design process, it is imperative that the mechanics of material removal be understood, regardless of whether the tool is rigidly mounted, passively compliant, or actively controlled. A survey of design efforts (Asada and Goldfine, 1985; Hickman and Judd, 1987; Hollowell, 1989; Hollowell and Guile, 1987; Kazerooni, 1988; Paul and FitzPatrick, 1986) reveals that these models are crucial to the design of an effective tool. Although in a strict sense these models may never be consulted directly by the advanced deburring system, their influence is embodied in the tool control laws.

Burr Identification and Measurement

Closely tied to the notion of burr modeling is burr measurement. Although it is hoped that accurate burr formation models will result in a clear picture of the distribution of burrs on parts before they reach the deburring cell, it is likely that the probabilistic computations will not coincide exactly with the burrs as they appear on a particular part. This is especially true for large burrs. For this reason, it is desirable to have some method for measuring the size and location of burrs prior to deburring, so that computed robot trajectories or tool selection may be altered to reflect actual burr conditions. Research using structured light techniques and computer vision (Whitney and Brown, 1987) has demonstrated the usefulness of this technique on weld seams. However, research is still lacking on methods to determine the size and location of smaller burrs formed during machining processes.

For the advanced deburring system to be effective, post-process measurements must be made and analyzed to determine if the process was carried out successfully. This is particularly important in the case of processes which may generate secondary burrs. If these burrs are unavoidable but predictable, their removal can be planned in advance. If they are unpredictable in either size, type, or location, post-process measurements must be made to determine their nature. This information is then fed back to the process planner, which determines the steps necessary for their removal. If the secondary burrs are deemed to be the result of improper tool performance, the tool parameters can be modified. In any case, the workcell controller must analyze the post-process measurements, determine acceptance, rework, or scrap, and schedule the proper actions.

Post-process measurements are also useful for low-bandwidth adaptive control. In principle, measurements of deburring results can be correlated with the models of burr removal to determine their validity. When discrepancies are noted, the models can be automatically updated and the rules reformulated. Furthermore, if active tool control is utilized, measurements of feature finish can be used to adjust setpoints in the tool controller to reduce chatter, control chamfer, gauge tool wear, and otherwise improve the quality of deburring.

TOOL DESIGN

In many robotic deburring systems, the robot carries deburring tools to the part, applying interference between a cutter and the edge. The cutter can be a rotary file, abrasive brush, countersink tool, grinding stone, or any material whose aggressiveness is put into relative motion against a part. Cutters are mounted in a spindle or motor used to supply rotation. Tool holders attach the spindle or motor to the robot, and may include passive compliance, sensors, or active control. If active tooling is used, a tool controller executes the control laws, adjusts setpoints, and performs sensory processing. The tool compliance, in both the cutter and in the tool holder, can eliminate chatter and accommodate for system inaccuracy and burr variations.

In other setups, the robot may carry the part to the deburring tools. Alternatively, functions previously associated with the tool holder may be performed by a part holder, such as a force-controlled table. Although some technical differences exist (for example, mounting a stationary workpiece on a force sensor eliminates inertial force components), each method performs the same basic task: moving the tool relative to the workpiece.

Robot Inaccuracy and Related Problems

Most industrial robots have a high *repeatability*, the ability to return to a previously recorded position when given the same coordinates. However, the ability of a robot to go to a position whose coordinates were computed, the *accuracy*, is low. While repeatability is limited by the mechanical qualities of the robot, such as joint backlash and motor friction, the accuracy is a function of the degree to which the robot controller's kinematic model reflects the actual arm. Although various calibration schemes can be used to increase robot accuracy (Ziegert and Datseris, 1988), the accuracy is lower-bounded by the repeatability, which cannot be increased without redesigning the robot. Furthermore, the overall positional error of the end effector is compounded by system inaccuracies such as part misalignment in the fixture, tool wear, machining discrepancies, and large part tolerances. Since the advanced deburring system paradigm requires that the robot accurately attain computed points, robot and system inaccuracies are important considerations.

Methods have been suggested which use sensory feedback such as force to determine the degree of tool-part contact, and adjust the robot position accordingly (Whitney, 1985). This is known as *through-the-arm control.* Unfortunately, large time delays in the robot controllers and low force resolution due to joint friction limit the effectiveness of the through-the-arm method. These shortcomings are commonly grouped into a single classification, *robot bandwidth*, which is a measure of the overall robot system response. The bandwidth is limited by the computational speed of the robot's controller, the communication protocol between computer and servo hardware, and physical quantities such as inertia of the robot links, motor response, and joint friction. Low bandwidth prevents the robot from responding to high-frequency control signals necessary for fine control of the tool.

The problem of robot inaccuracy can be reduced by calibration or circumvented by through-the-arm control, but neither provides the performance required by many deburring applications. For this reason, accommodation for errors by the cutter or tool holder is necessary. This may be implemented with passive or active compliance in the tool holder, or natural compliance in the cutter. When active tooling is used to increase bandwidth, this is known as *around-the-arm control*.

Cutter Considerations

The cutters used in robotic deburring can be classified as either compliant or non-compliant. Compliant tooling includes abrasive-loaded nylon brushes, buffing wheels, and other materials which produce a radius on the edge. This is often preferable to a chamfer. This tooling tends to produce less secondary burrs, which is another advantage. Unfortunately, these cutters do not remove material quickly, and are therefore limited to small burrs or soft materials such as aluminum and brass. Compliant tooling is also prone to considerable wear, which must be accounted for by the robot trajectory planner. In addition, the bulky nature of these cutters prevent their use in tight corners or deep contours.

Non-compliant cutters include carbide burs, rotary files, and grinding stones. This tooling is aggressive, and can be used for chamfering of hard metals and for dimensioning of weld beads and castings. However, these hard tools produce secondary burrs, and often cause chatter. The chatter can be later smoothed with compliant tooling, but this requires extra processing. If the deburring is not carefully monitored, the aggressiveness of non-compliant tooling may ruin the edge. Less importantly, grinding stones wear, and rotary files can become filled with machined material, reducing their effectiveness.

Compliance is important to the advanced deburring paradigm. Naturally compliant cutters such as brushes can be used on robots which have been improved with calibration. Hard cutters, however, require compliant tool holders to compensate for robot inaccuracies. These holders can either be passive spring-damper systems, or active devices which can be precisely controlled in response to forces or other signals generated during deburring.

Tool Holders

Hard cutters require compliant tool holders, either passive or active, which perform three functions: keeping the tool on the part despite robot and system inaccuracies, accommodating burr variation, and eliminating chatter. When deburring machined parts, accounting for robot positioning inaccuracy in order to keep the tool on the edge often dominates the accommodation for variation in burr size. In contrast, the effect of burr size variation when dimensioning outweighs most robot and system inaccuracies. In both cases, however, chatter is caused by the inappropriate choice of compliance.

In contrast to machine tools, whose structural stiffnesses are high in all directions, the relatively low stiffness of robot arms allow large-amplitude resonances which cause chatter. Asada and Goldfine (1985) 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 selection of the 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 holder and the robot, a tool holder must have an axis with stiffness less than a tenth of the stiffness of the robot. The robot must also keep this axis either normal or tangential to the workpiece.

The choice of stiff axis depends upon the application. When dimensioning, stiffness is highest in the normal direction so that large burrs can be removed. In this case, the edge will be machined along the robot trajectory. The final dimension of the part depends on the accuracy and repeatability of the robot. In contrast, when deburring machined edges, robot repeatability (and therefore accuracy) is not sufficient for edge following. 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. For one-degree-of-freedom tool holders the robot path must be planned to insure that the stiff axis is oriented in the proper direction.

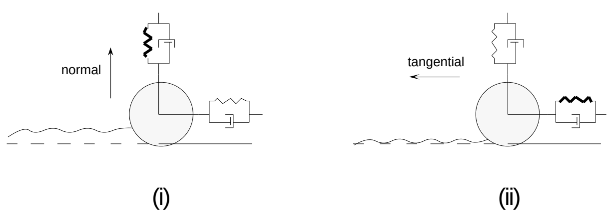


Figure 2. The 10:1 Rule. To reduce chatter, normal and tangential stiffness of the tool holder should differ by an order of magnitude or more. In dimensioning, the normal stiffness is often larger (i). In precision deburring, the tangential stiffness is often chosen higher (ii).

An improvement over the one-degree-of-freedom tool holders are holders whose compliances are designed into both axes. Hollowell (1989) reports the results of a tool compliant in the normal direction and stiff in the tangential direction. Tooling investigated by Kazerooni (1988) is compliant in the normal direction, yet even more compliant in the tangential direction. This allows the tool holder to accommodate large burr variations. Others, however, do not follow the 10:1 rule (Bausch *et al*., 1986), yet report good results with equal compliances in both directions. The discrepancies between these reported results indicate that the mechanisms underlying compliance need more thorough study.

Compliance can be implemented both passively and actively. Appearing earlier in industry than active holders, passive holders have some advantages. They are simpler, cheaper, often weigh less, and require no additional controller. References (Asada and Goldfine, 1985; Bausch *et al*., 1986; Gillespie, 1987) describe the applications of some of these passive tool holders.

Around-the-arm control using active tool holders is beginning to appear in industrial applications, but is still principally a research topic. Active tool holders have several advantages over passive tool holders. Their compliances can be changed for different materials or burr conditions. Some impedance transfer functions (stiffness as a function of frequency) cannot be obtained with passive elements, and can only be realized with active devices. Furthermore, a robot must physically rotate passive tool holders to effect a change in normal axis orientation. The compliances of an active two-degree-of-freedom holder can be changed electronically at high speeds, allowing for close following of complex edges at a constant feed rate.

Many schemes have been proposed for active control of deburring tools. These include hybrid force/position (Hollowell, 1989), impedance (Kazerooni, 1988), vision (Whitney and Brown, 1987), and acoustic emission (Dornfeld and Masaki, 1987). The tool controller may be independent from the robot controller, or integrated with it. Integration is required when the tool holder must change the direction of compliance electronically during deburring, or when process information flows into the robot controller. This flow must occur when the cutter is nearing its range of actuation while compensating for robot inaccuracy. In this situation, the robot must move in the direction that will place the cutter back in the center of its actuation range. The integration of tool and robot controllers also supports more sophisticated workcell architectures. Sensory feedback from deburring can update the knowledge base or world model referenced by the process planner, as a form of low-bandwidth adaptive control.

Finally, it is important not to overlook the possibility of increasing stiffness and accuracy through the use of tool jigs, which form a closed kinematic chain between the robot and the part fixture. It has been shown that such techniques result in significant improvements in dynamic response when applied to chipping operations (Asada and Ogawa, 1987). Loucks *et al*. (1989) have demonstrated satisfactory results when chamfering aluminum, by using tool guides which provide stabilization and precise alignment between the cutter and the part. What is significant is that stabilizing contact between the robot and the part aids in increasing accuracy and stiffness.

AUTOMATED PROCESS AND TRAJECTORY PLANNING

Robots in industry are usually programmed by teaching, a process that is tedious and time consuming. An alternative approach is to compute the desired robot coordinates directly, a method known as *offline programming*. Some advantages of offline programming include a reduction in the time necessary to generate robot coordinates, the ability to develop and test robot programs in simulation, and a considerable reduction of robot downtime. Unfortunately, robot coordinates which are computed offline are often unusable without touchup due to several sources of inaccuracy. As previously noted, the overall positional error of the end effector is due mainly to robot inaccuracy, but errors in machining, large part tolerances, tool wear, and part misalignment in the fixture can also contribute to the problem.

Offline programming systems may be a significant improvement over conventional teach programming techniques, even when touchup is required. However, full automation of the deburring process is not possible with these systems, since a human operator is required at the programming interface. The tenet of the advanced deburring system paradigm is that usable robot paths can be generated from data automatically, with no human intervention. This is possible with the incorporation of expert systems, which encapsulate the knowledge of the human operator at the offline programming interface.

The expert systems necessary for producing the data traditionally generated by humans are the process planner and the trajectory planner. The process planner is responsible for producing a list—an association of tools and tool parameters with each feature of the part. The tools may include naturally compliant abrasive brushes, cutters in passively compliant holders, or sophisticated active tools. The tools are all available to the robot through quick change adaptors, devices commonly used in industry which enable a single robot to “snap on” a variety of end effectors, including grippers for part handling. The process planner fills out the list by extracting each feature from the description, reading the machining operations which formed the feature, and consulting models of burr formation to predict likely burr types, sizes, and locations.

The trajectory planner is responsible for computing robot coordinates, but it must first partition the list into a set of logical operations. Before deburring can take place, the trajectory planner must determine the part handling and fixturing sequences which must be performed in order to make each feature reachable by the tool used to deburr it. This is in general an unsolved problem, but considerable research effort has been expended (Lozano-Perez *et al*., 1989) to develop algorithms which apply within broad limits. Once this sequence has been developed, it is mapped into robot coordinates using mathematical transformations.

The generation of robot coordinates for deburring proceeds in a similar manner. For each configuration of the part in a fixturing device, the trajectory planner groups edges which can be deburred with a particular tool, and transforms this information into robot coordinates. These coordinates are combined with the tool type, parameters, and suitable approach and depart points to completely specify the actual robot trajectories for deburring.

Through-the-arm Control

A process is considered forgiving if it is unaffected by inaccuracies. If a deburring process is forgiving (such as brushing), only moderate attempts must be made to compensate for robot inaccuracy. The use of through-the-arm control is therefore feasible. During this type of control, sensed error is fed back to the robot controller, which alters the computed path in the direction necessary to reduce the error. Since most robots are position-controlled machines, and the bandwidth due to arm inertia, backlash, and controller cycle times is low, the error correction can only be moderate and infrequent.

If the process is demanding, such as the precision deburring of hard metals using a rotary file, through-the-arm control is unsatisfactory, and the around-the-arm method must be used to improve bandwidth. However, it is often necessary to update the robot position when the errors sensed by the tool controller lie outside the range of tool's compensation. With this method, the robot is used as a gross positioning device which has the capability of altering its position infrequently due to sensed error signals. The tool is used as a fine positioning device which is capable of precise edge following.

Modifications

Evaluation of burr conditions immediately prior to deburring allows the tool controller to modify the control parameters based on the perceived size and type of the burrs. In cases where large burrs are sensed, this may mean increasing the stiffness in the tangential direction relative to that in the normal direction. In cases where burrs are perceived to be small, the opposite action would be taken. Furthermore, preprocess determination of the actual locations of burrs can be used to tune the probabilistic burr formation models used by the process planner.

Techniques for inspecting the characteristics of the edge immediately after processing are useful for several reasons. These post-process measurements can be used to determine if the part has been scrapped or must be reworked. Such measurements can be fed back to the tool or robot controllers to allow gains or paths to be adjusted so that scrap or rework will not occur in subsequent runs.

EXAMPLES

At the Automated Manufacturing Research Facility of the National Institute of Standards and Technology (NIST), a deburring cell has been developed which demonstrates the deburring of parts based on their description and a graphically-developed process plan (Murphy *et al*., 1988; Norcross, 1988; Proctor *et al*., 1989). This cell, the Cleaning and Deburring Workstation (CDWS), is capable of deburring roughly prismatic aluminum and brass parts.

The CDWS consists of a workstation controller, two robots, various quick-change deburring tools, a rotary vise for part fixturing, and a part transfer station. The workstation controller is a set of software modules which support process planning and task scheduling. A six-axis hydraulic robot is used for part handling and buffing. A six-axis electric robot is fitted with a quick-change wrist, and can select between a rotary end brush, a countersink tool, a hole brush, and a gripper. The vise can be rotated to any of three perpendicular orientations, which reduces the amount of robot motion required for part refixturing and deburring. The part transfer station consists of two roller tables which can transfer trays of parts between the CDWS and material storage.

In addition to automating deburring, methods of automating buffing and part cleaning are being investigated. A interface is used to develop a process plan and robot trajectories for buffing, in a method similar to that used for deburring. Cleaning is currently implemented as a simple part handling task, during which parts are placed into a washing unit and emerge at a known location. The complete layout of the CDWS is shown in figure 3; however, buffing and cleaning will not be discussed in detail.

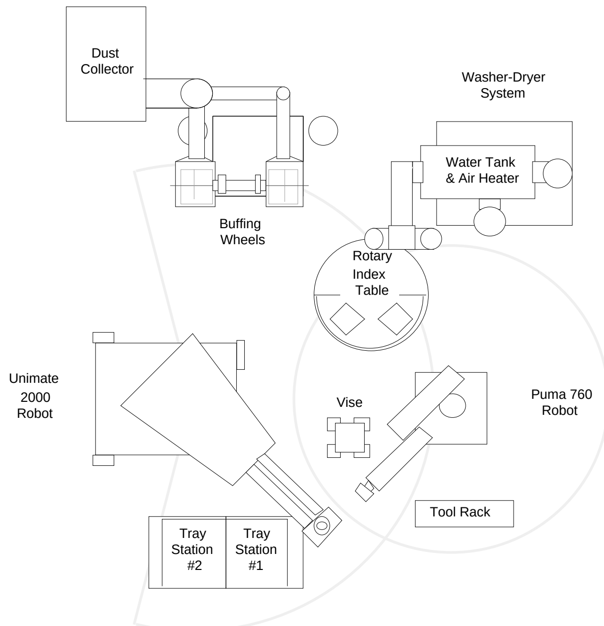
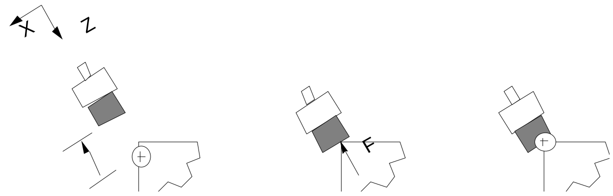


Figure 3. The Cleaning and Deburring Workstation floor layout.

The process plan is developed by a human expert at a graphics terminal. data is used to draw images of a part on the screen. Using a mouse pointing device, the user can select features to be deburred, and associate tools and tool parameters to each feature. Positions of the grippers can also be selected relative to the part using the mouse, as well as the desired locations of the part in the rotary vise (the location of the part in the roller table is assumed to be known). Once this process plan is developed, a trajectory planner computes robot locations. Straight edges are defined by their endpoints, while arcs are approximated with straight-line segments. The robot linearly interpolates the intermediate positions. The center of the vise is a single taught point, which serves as a reference from which all coordinates are specified.

Since industrial robots are inherently inaccurate, it is known *a priori* that the computed robot coordinates will not result in satisfactory motion. Two methods are used to increase the accuracy of the robots. For the part handling robot, an error map is constructed empirically, resulting in a table of errors for given coordinates. When the robot is told to move to specific coordinates, the error table is consulted and the coordinates are scaled by the appropriate amount so that the resultant motion is more accurate.

For the deburring robot, passive compliance in the tool x-y plane make the tools self-centering for countersinking and hole brushing operations. A two-pass force sensing technique is used when deburring with the end brush. On the first pass, the robot approaches each computed point about two centimeters back in the tool z direction, then drives the tool forward until a desired force is attained. The robot controller is then instructed to record the current joint angles. This procedure is known as *self-teaching*. Once each computed point has been corrected, the robot interpolates between them, deburring the part. This process is shown in figure 4.



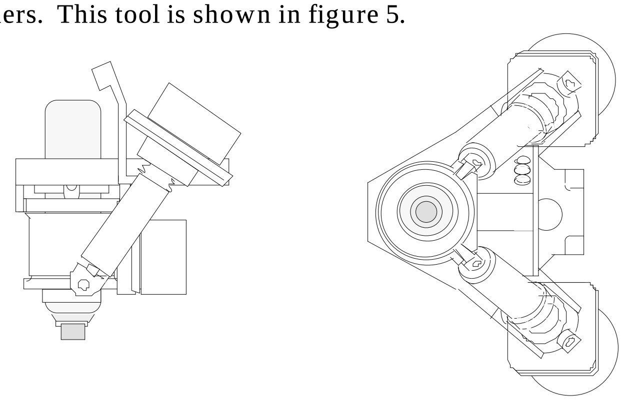
(i) (ii) (iii)

Figure 4. Self-teaching. The robot approaches the computed point (i), moves forward until a specified force is met (ii), then records the new point in place of the original (iii).

Self-teaching is essentially a calibration method. Although position errors do occur during the straight-line interpolation between computed points, the natural compliance of the brushes easily accounts for these small differences.

While this system demonstrates a substantial savings in time when compared with teach programming, it is still far from fully automated: a human expert is still required for the selection of edges, tools, and part handling and fixturing data. Furthermore, only soft metals such as aluminum and brass can be deburred, since harder metals require non-compliant cutters which have been shown to generate chatter when used with the CDWS robot. An improvement over this system is being jointly developed by NIST and the United Technologies Research Center (UTRC) as part of a solution for the automated deburring of aerospace parts for the U.S. Navy.

As an extension of the CDWS, this cell will incorporate -based programming automation, with the addition of active hard tooling to compensate for errors in the computed trajectories. The tooling consists of a high-speed spindle and rotary file mounted in an active housing, which is gimbaled to provide two degrees of freedom. Transducers and sensors monitor the forces felt by the tool tip and the current excursion of the tool tip from its center location. Hybrid force and position control laws allow for compliances and stiffness to be varied in the normal and tangential directions. In addition, the orientation of the tool's normal vector can be specified continuously, allowing for the following of complicated edges and sharp corners. This tool is shown in figure 5.



(i) (ii)

Figure 5. The Adaptive Deburring Tool. Side view (i), and bottom view (ii). The robot wrist would appear horizontal.

The operation of this tool has been described by researchers at UTRC (Hollowell, 1989). In their system, trajectories are computed offline and downloaded to a robot. The points are then edited using a teach pendant to ensure that positional errors are not too great for the tool to correct. A program executing in the robot controller guides the tool along a complicated edge, while independent force and position servos control the fine motion of the tool. The tool is stiffer in the tangential direction than the normal direction, as suggested by Asada and Goldfine (1985). The servo signal normally controlling the position of the sixth robot axis has been diverted to the tool controller, and serves as a reference for the normal and tangential directions. Because of this, the tool does not have to be physically rotated as it follows a sharp corner in order to keep its compliance normal to the edge, but rather the compliance of each axis is actively controlled to achieve this effect.

Another automated deburring system, the Robotic Edge Finishing Laboratory, has been developed at Sandia National Laboratories (Loucks *et al*., 1989). This cell consists of a calibrated five-axis SCARA robot, and a system from which robot trajectories are computed. A vision system determines the orientation of the part to be deburred, and a force system integrated in a robot controller supports self-teaching and edge following. The cell is capable of brushing operations, as well as producing precision chamfers of 0.3 ± 0.1 millimeters on aluminum.

Before the part is deburred, its geometric description is developed using the system. A conversion utility is applied to the edges, resulting in code suitable for CNC machining centers. A supervisory program extracts edge information from this code for use with the robot. Once this data is generated, the cylindrical part is fixtured in a three-jaw chuck with its axis vertical, so that only its rotation about this axis is unknown. The vision system compares its image to the model, searching for a notch. The position of the viewed notch is used to compute the orientation of the part to within one-half degree. The edge information from the model is transformed into robot coordinates based on this complete knowledge of the fixturing to generate actual robot locations.

A self-teaching technique similar to that employed in the CDWS is used for error compensation when deburring with brushes. The natural compliance of the brush ensures that adequate interference is provided along the edge. This is especially important in cases where a curved edge is approximated with short line segments. To account for errors when chamfering with an end mill, two methods are used. A tool guide houses the end mill, allowing for cutting only to a preset depth. Two-axis force sensing helps to align the tool properly at the edge. When the tool is aligned, a through-the-arm servo is executed via force feedback to the robot controller. The through-the-arm method is feasible in this case due to the use of the tool guide.

SUMMARY

Improvements in deburring technology are required for the development of fully automated manufacturing systems. The need for improvement is manifest in three areas: the measurement and modeling of burr formation and deburring mechanics; the use of sensory feedback for intelligent tool and robot control; and the automation of process planning. Their importance is evident when considering an automated deburring system paradigm. In this system, robotic deburring trajectories are computed offline, based on machining data. An expert system process planner consults models of burr formation and removal to generate a list of burr sizes and types likely to be found on each feature of the part. Models of burr removal are then used to associate tools and tool parameters to each feature. A trajectory planner takes this list of features and tools, mathematically transforming the coordinates to robot trajectories for part handling and deburring. Errors which result from robot inaccuracies and system errors such as machining discrepancies, tolerances, and part misplacement are corrected at runtime using a variety of techniques. These methods range from the use of natural and passive compliance to self-teaching and active tool control.

Researchers at the National Institute of Standards and Technology, United Technologies Research Center, and Sandia National Laboratories have developed subsets of this paradigm. Although these facilities demonstrate the viability of an autonomous deburring cell, they fall short of full automation. Their shortcomings are evidence of the need for further research in several areas. At the lowest level, measurement and modeling, these research issues include:

- broadening the scope of burr formation and removal models, both empirical and analytical;
- measuring the size and distribution of small machined burrs;
- gauging the results of edge breaking operations to determine if chatter or secondary burrs have been produced;
- and integrating the above measurements into realtime control of deburring.

Building on the above, tool design research extends into the following:

- improving the aggressiveness of soft tooling to achieve high material removal rates while benefiting from compliance;
- understanding more fully the effects of compliance on deburring;
- formalizing the use of tool jigs and fixtures;
- and broadening the selection of signals used for active tool control.

The performance of robots impacts significantly on the capability of the deburring cell. To improve this performance, research must address:

- automating robot calibration;

• determining the actual position of the end effector in real time;
• quantification of system inaccuracies;
• and integrating realtime path modification into robot controllers.

At the highest level, process planning and cell control issues include:

• formulation of expert system algorithms for edge characterization, tool selection, and trajectory computation;
• and development of workcell architectures which support full automation.

It is hoped that the perspective provided by the advanced deburring system paradigm will encourage research into these areas.

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