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AGILE ROBOTIC EDGE FINISHING SYSTEM RESEARCH*

By: Mark A. Powell
Senior Member of the Technical Staff
Sandia National Laboratories
Albuquerque, New Mexico

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One SME Drive, P.O. Box 930
Dearborn, Michigan 48121-0930

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ABSTRACT*

This paper describes a new project undertaken by Sandia National Laboratories to develop an agile, automated, high-precision edge finishing system. The project has a two-year duration and was initiated in October, 1994. This project involves re-designing and adding additional capabilities to an existing finishing workcell at Sandia; and developing intelligent methods for automating process definition and for controlling finishing processes. The resulting system will serve as a prototype for systems that will be deployed into highly flexible automated production lines. The production systems will be used to produce a wide variety of products with limited production quantities and quick turnaround requirements. The prototype system is designed to allow programming, process definition, fixture re-configuration, and process verification to be performed off-line for new products. CAD/CAM (Computer Aided Design/Computer Aided Manufacturing) models of the part will be used to assist with the automated process development and process control tasks. To achieve Sandia's performance goals, the system will be employ advanced path planning, burr prediction expert systems, automated process definition, statistical process models in a process database, and a two-level control scheme using hybrid position-force control and fuzzy logic control. In this paper, we discuss the progress and the planned system development under this project.

* This work performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract DE-ACO4-94AL85000.

1.0 INTRODUCTION

Sandia National Laboratories is a Government Owned-Contractor Operated Department of Energy (DOE) Laboratory. Sandia's primary mission is the development and stewardship of the nation's nuclear weapon stockpile. Since the late 1980's, Sandia National Laboratories has been interested in developing an automated robotic edge finishing system for the production of high precision metal parts. The bulk of the edge finishing on these parts is currently performed manually using modified dental instruments. Sandia is interested in automating the precision finishing process to free workers from the tedious, undesirable, and sometimes dangerous task of manual edge finishing and to improve the consistency of the products. In addition, production schedules and projected stockpile needs for precision components indicate that future production runs will be smaller than the historical levels (200-5000 total) and the required production rates will be highly variable (0-1000/yr.). There is a need to manufacture a large variety of similar components on the same production equipment, in order to level the production loads and use equipment more efficiently.

One of the strategies for meeting future production needs is to develop and deploy agile automated production systems that can be quickly reconfigured for new and different product requirements. Sandia would like these systems to allow programming, process development, and initial process verification to occur off-line. This would enable the process definition task to be initiated while still producing another product. The new process parameters would then be available for downloading and execution immediately after the workcell is physically reconfigured and the new parts begin entering the workcell. Even if the initial process parameters are not optimal due to inaccuracies in the specification technique, these parameters would serve as a good starting point for the first production runs. In this way, the development time required to fine tune a process could be reduced or, in the ideal case, eliminated. In addition, true system agility requires that the mechanical fixturing and tooling are designed for flexibility to allow re-tooling and change-over to be achieved quickly when new products are introduced.

The number of finishing processes, materials, and machining processes that could be included in process databases is huge. Therefore, this project is designed to demonstrate most or all of the capabilities that an agile finishing system should possess on a subset of the finishing processes and machining histories that are possible for a part. The software that is being developed for this project is intended to operate from extendible databases that allow additional process models to be added as information becomes available.

2.0 System Architecture

The agile finishing system's performance goals map into four major development sub-tasks: Burr Size and Location Prediction, Process Modeling and Planning, Path Planning, and Real-time Process Control. In addition, there are engineering tasks that are required to enable the development process to proceed smoothly: workcell mechanical design and system integration. This project uses technologies developed in previous Sandia projects and extends the technologies to meet the agile edge finishing system's requirements. Figure 1 is a diagram showing the major project development areas and the type of information that must be passed between each of the system software modules. All software modules are required to operate on a single CAD solid model of a production part. As many functions as possible will be performed using the capabilities of Sandia's corporate CAD/CAM system. Custom code will be kept to a minimum and what code is developed will run under the CAD system's menu structure using menu development tools provided with the system. The CAD/CAM system chosen for this project is the Pro/ENGINEER, Pro/MANUFACTURING, and Pro/DEVELOP[1] software system. These software packages comprise Sandia's corporate standard CAD/CAM system and were chosen for this project to maintain compatibility with the corporate part database.

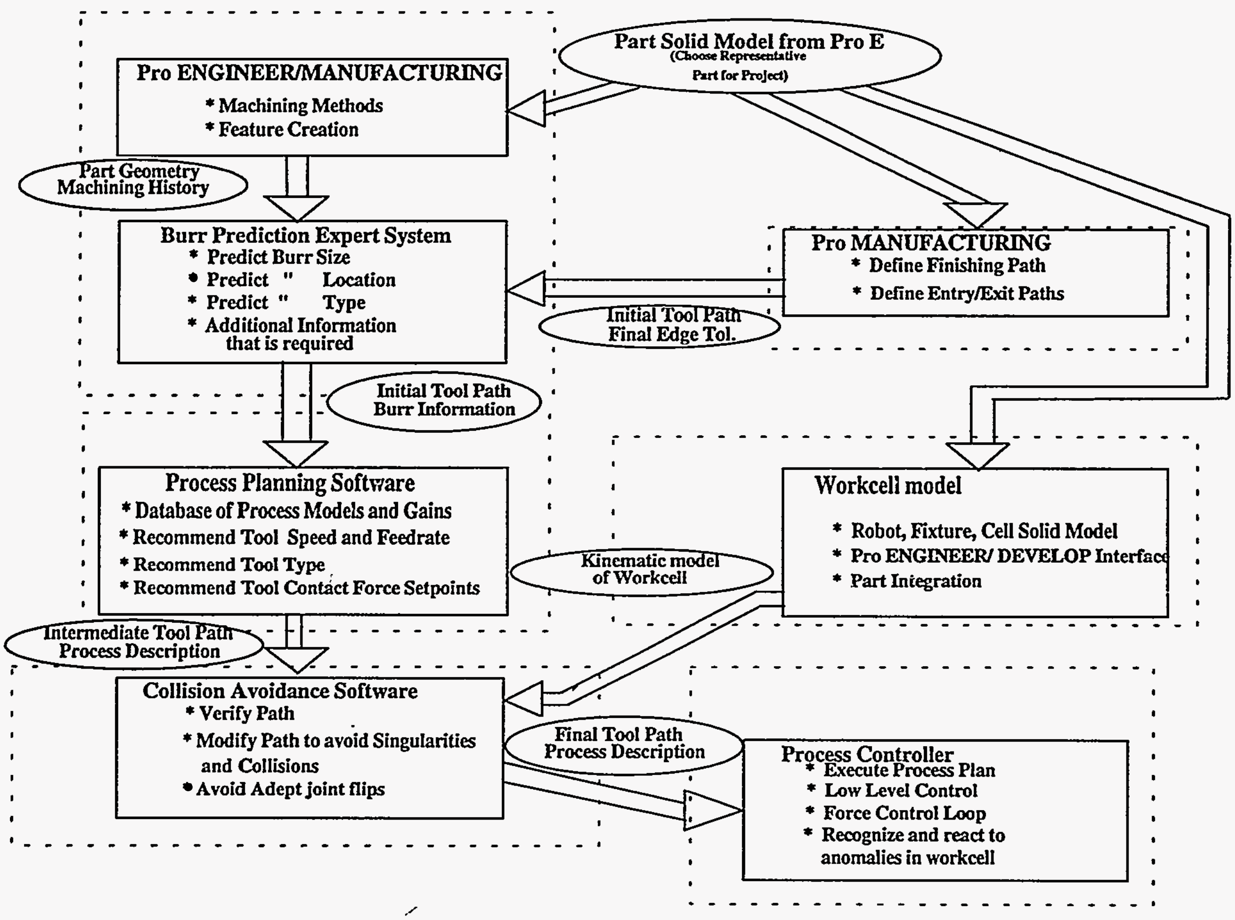

Figure 1: Agile Edge Finishing System
Structural Framework

2.1 System Integration and Information Flow

This task is necessary to ensure that all software modules developed in this project are compatible with one other, Sandia's corporate database, and the ease of use goals for this project. For these reasons, all of the software modules are required to operate on a solid model developed in Pro/ENGINEER and operate under a common menu structure defined using the capabilities of Pro/DEVELOP. Information is passed between software modules using a data representation

[1] Trademarks of Parametric Technologies Corporation, Waltham, MA.

format called a hyperpoint. Each point along the tool path is represented by a set of {x,y,z,i,j,k} positions in the first six channels of the hyperpoint. Additional information (such as burr size and type) required for the next processing step in the system is appended to the path points as additional data channels.

2.2 Workcell Design and Initial Toolpath Definition

This is the first operator task undertaken when definining a finishing process for a part. The purpose of this task is to define an initial tool path, define a desired edge chamfer, construct the 8-channel hyperpoints necessary for the next step, and pass the hyperpoints to the downstream software module.

The initial tool path is derived from a CNC file generated using Pro/MANUFACTURING. Pro/MANUFACTURING is currently resident on an engineering workstation that has a serial connection to the Adept robot controller in the finishing workcell. A modular fixturing system has been integrated into the existing finishing workcell (See Figure 2). A CAD solid model of the fixturing system has been defined. The fixturing system is reconfigured and the part is assembled into the fixture in the virtual CAD/CAM environment. Figure 3 shows a CAD model of a valve body assembled into the fixturing system. The tool path is then defined using coordinates defined relative to a machining coordinate system placed on the modular fixturing baseplate. The manufacturing process is defined, the features to be created are chosen, and then Pro/MANUFACTURING generates CNC code that defines the process tool-path. The resulting CNC file is post-processed to extract the {x,y,z,i,j,k} components of the tool path. The software then constructs 8-channel hyperpoints containing the tool path points, move type (in-contact, not in-contact), and the desired final edge condition. Currently, the desired final edge condition is input by the operator, not deduced from the CAD model. This feature will be added at a later date.

All tool path points are defined in the CAM system using a machining coordinate system placed on a corner of the modular fixturing system. Within the physical workcell the robot BASE coordinate frame is translated to the corresponding corner of the physical fixture. In the robot control system, all path points and motion commands are defined and executed relative to the location of the BASE frame. In this way, the path positions defined by the CAM system are in registration with the physical workcell and can be executed by the robot without additional processing. This aids in the re-configuration and re-programming of the system. Figures 4a and 4b show the location of the machining coordinate system within the CAM model and the location of the BASE frame within the workcell.

Once it is defined, the operator may animate the process and view a tool-only representation of the finishing tool path. Figure 5 shows an animation of a finishing process on a test coupon. Once the process has been verified at the tool-only presentation level, the hyperpoints will be passed onto the next module in the system.

2.3 Burr Size and Location Prediction

The software produced for this task takes the machining history of the part and predicts the as-machined edge condition of the part as it comes into the workcell. The software then adds three

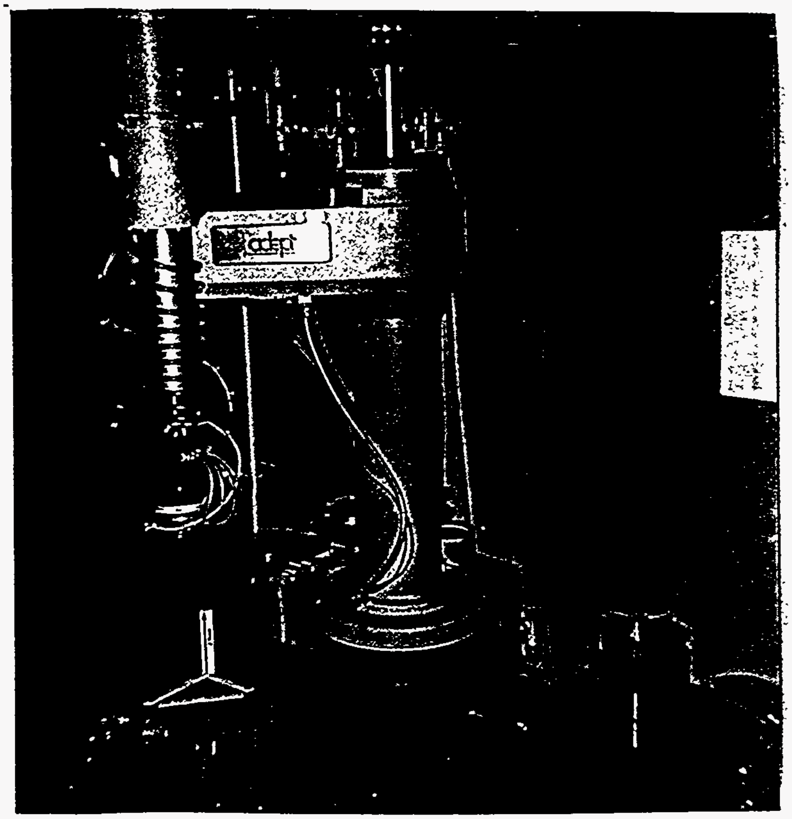

Figure 2: Sandia Robotic Edge Finishing Workcell

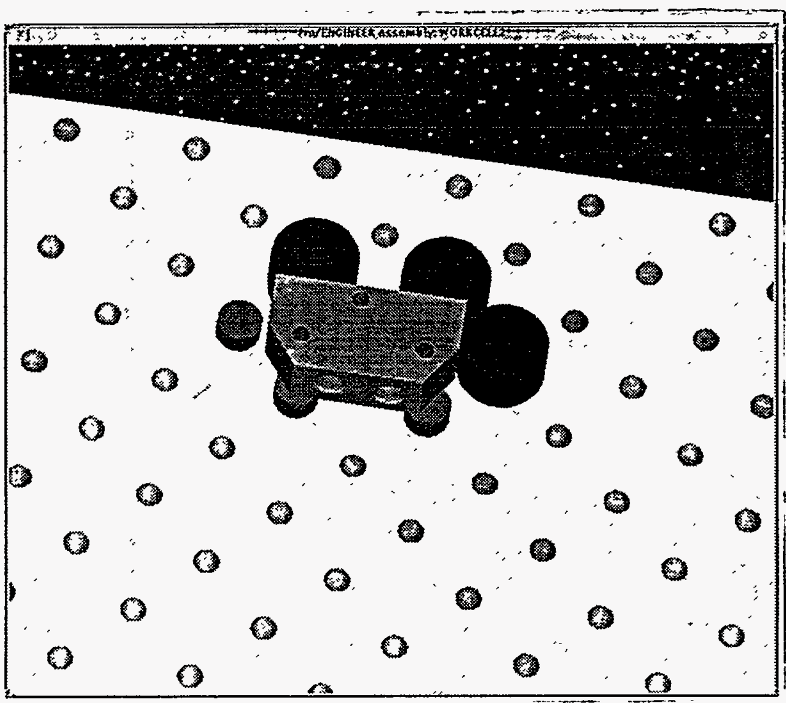

Figure 3: Test Part Assembly: Valve Body in Modular Fixturing System

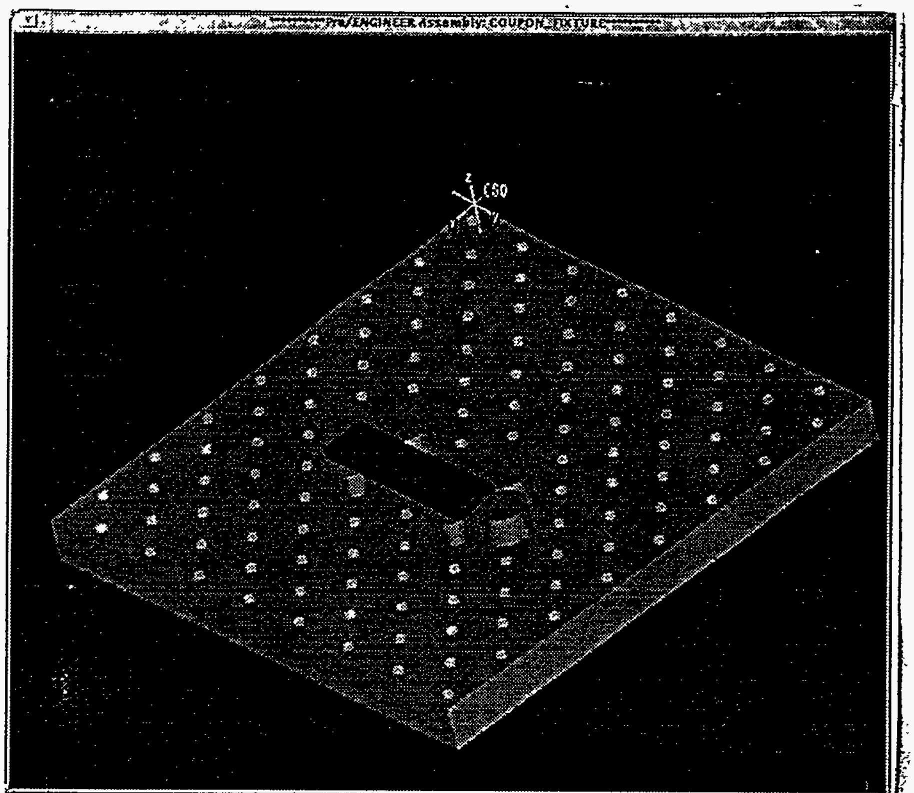

Figure 4a: Machining Coordinate System Placement in Pro/MANUFACTURING

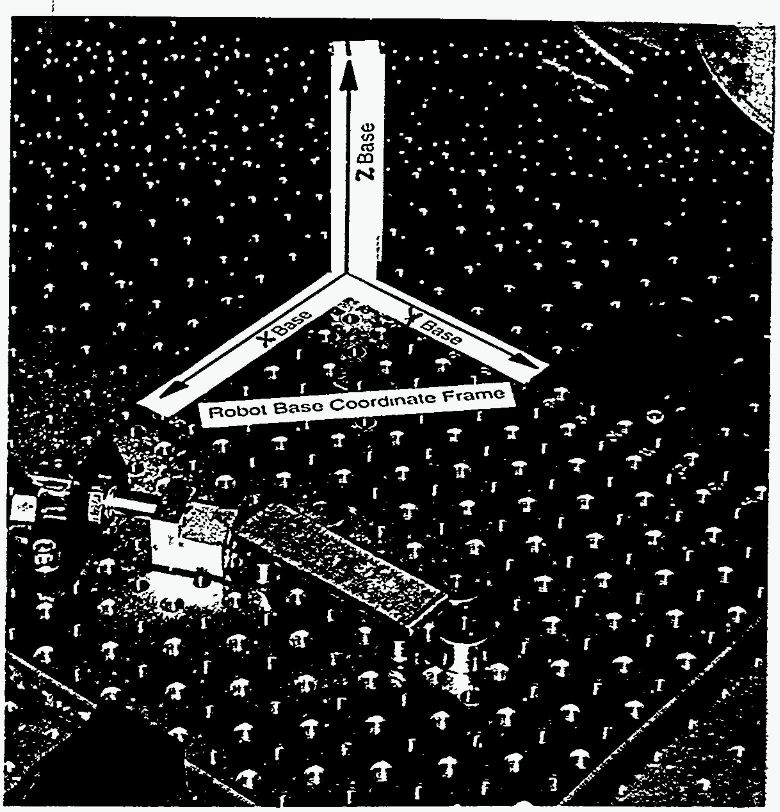

Figure 4b: Robot BASE Frame Placement Within Finishing Workcell

channels of information, describing the burr type and dimensions, to the tool path points. The resulting 11-channel hyperpoint is then passed to the process planning module. The purpose of the burr size and type prediction module is to provide information to the process planner. This information will enable the amount of material that must be removed from the edge at each tool path point to be estimated. The process planner uses the material removal volume to calculate the process parameters.

The bulk of the work on this software module is being performed at the University of California-Berkeley (UCB) by a group of researchers led by Dr. David Dornfeld. The development work on this module is leveraged off of previous work Dr. Dornfeld's group performed for the Consortium on Deburring and Edge Finishing (CODEF). The interfaces between the UCB software and the Pro series of software packages are being developed by Jim Hachman and Tracy Walker at the Sandia, California facility.

The UCB software is designed to use CAM data of a part and definition of a machining process to predict the post-machining edge condition of the part (i.e. burr type and location). This qualitative approach is being extended to allow quantitative predictions of the post-machining edge condition (i.e. burr type, size, and location). The probable burr size and locations will be determined using an empirical model of the machining process. Initially, the predictions will be valid only for face milling processes, but later will be extended to include other types of milling processes.

The software is being modified to extract the machining history for a part from the CNC files that were used to fabricate the part. Then the part geometry is input from the Pro/ENGINEERING solid model; the initial toolpath hyperpoints are read; the burr parameters at each of the path points are predicted; and 11-channel hyperpoints {x,y,z,i,j,k,tool contact/no contact, desired chamfer depth, burr type, burr height, burr width} are constructed. If the UCB software predicts a discontinuity in the post-machining edge condition along the tool path, such as the burr type toggling from primary to secondary, the software will interpolate and insert another hyperpoint into the path where the transition occurs. Figure 6 shows graphical output from the burr prediction software for a face milling process on a prismatic part with four holes drilled in it. The black areas attached to the edges of the part are an indication of the relative size of the burrs predicted to result from the face-milling process. Once constructed, the 11-channel hyperpoints are ready to be passed on to the next module in the finishing system.

The model used for the graphical representation in Figure 6 was developed for demonstration purposes only and was not empirically derived. UCB is currently running tests to derive the empircal relationships between tool exit angles and burr size and incorporate the new models into their software.

2.4 Process Planning and Modeling

This module is designed to assist with off-line development of the process parameters needed to define an automated finishing process. This module will use a database of empirical process models to pick candidate processes and determine the required process parameters. The first process has been characterized using an XYZ-table as a test bed. Testing is currently underway

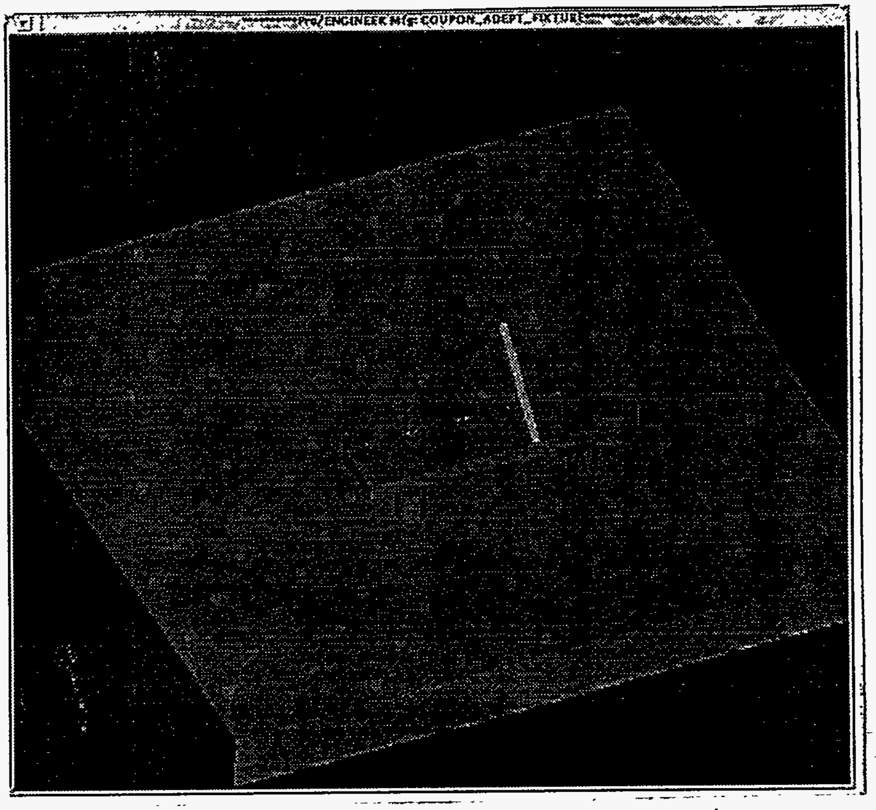

Figure 5: Tool-Only Process Animation Gouge Verification

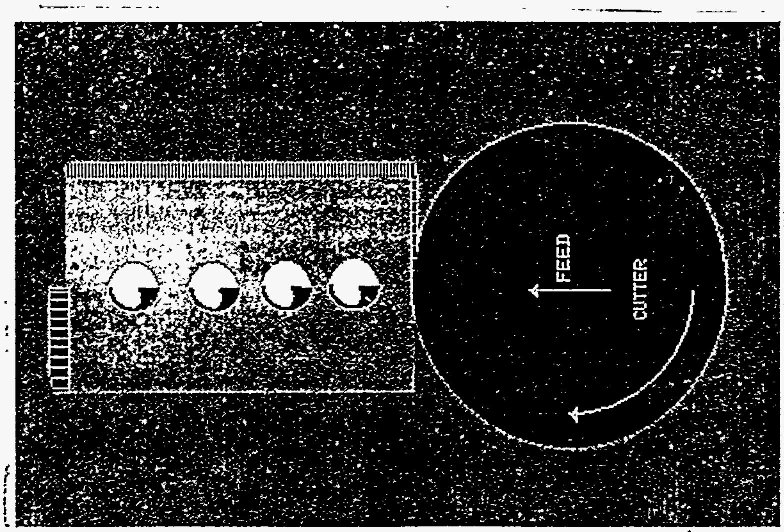

Figure 6: BURR EXPERT Graphical Output (Courtesy of UCB)

to determine the empirical relationships for the first process to be characterized in the robotic workcell (Figure 7). The output from the process planning and modeling module is a set of 10-channel hyperpoints {x,y,z,i,j,k,tool contact,F,FR,tool} that are passed on, ready for execution, to the automated finishing system or the path planning module.

The planning module will calculate the volume of material that must be removed per unit length using the desired edge condition and burr size prediction channels of the in-coming hyperpoints. Once the process selection is made, the material removal volume and the corresponding process model from the database will be used to calculate the feedrate (FR) and tool force setpoint (F, tangential or normal) at each point along the tool path. Each tool path point will have a set of process parameters attached to them using the hyperpoint data construct.

The empirical process models will consist of a set of equations of the form:

$$\sum_{m=1}^{n}\sum_{p=m}^{n}(b_{mp}X_mX_p) + \sum_{m=1}^{n}(b_mX_m) + b_o \qquad (1)$$

where,

X_m, X_p = the process parameters (tool forces and feedrate, initially)
b_0, b_{mp}, b_m = constants derived using a regression fit to the data points
Y_m = the control variable (in this case material removal rate in volume/unit length)
n = the number of control parameters

One equation will be derived for each of the following tool force parameters: mean normal tool force, mean tangential tool force (see Figure 8), and the standard deviation of each of these force components from the mean during process execution. One mean force will be a controlled parameter during execution of the finishing process. The other mean force and the standard deviations will be monitored by a fuzzy rule-based control loop that will be discussed in more detail later. The force component that will be monitored and the one that will be controlled depends on the final configuration of the hybrid position-force control loop in the low-level control system.

A bounding function will also be defined for each process. The bounding function represents the acceptable process boundary for the system. Beyond the boundary, the system will no longer produce acceptable edge results or the process requirements will exceed the finishing system capabilities. Processes operating in the unacceptable region may result in unwanted tool chatter, secondary burrs, or damaged tools; or have higher power requirements than the spindle is capable of producing. The bounding function and the process model equations are solved to yield the process parameters at each tool path point. This approach will yield a feedrate, force pair that is at the highest feedrate allowed by the bounding function, yet is still executable and produces acceptable edge results.

A 3-axis XYZ table was used as a test bed for the development of the process modeling procedures. The XYZ table was used to characterize a process using a right angle fluted bur rotating at 60 kRPM. Figure 9 shows the raw data and the curves that resulted from a regression

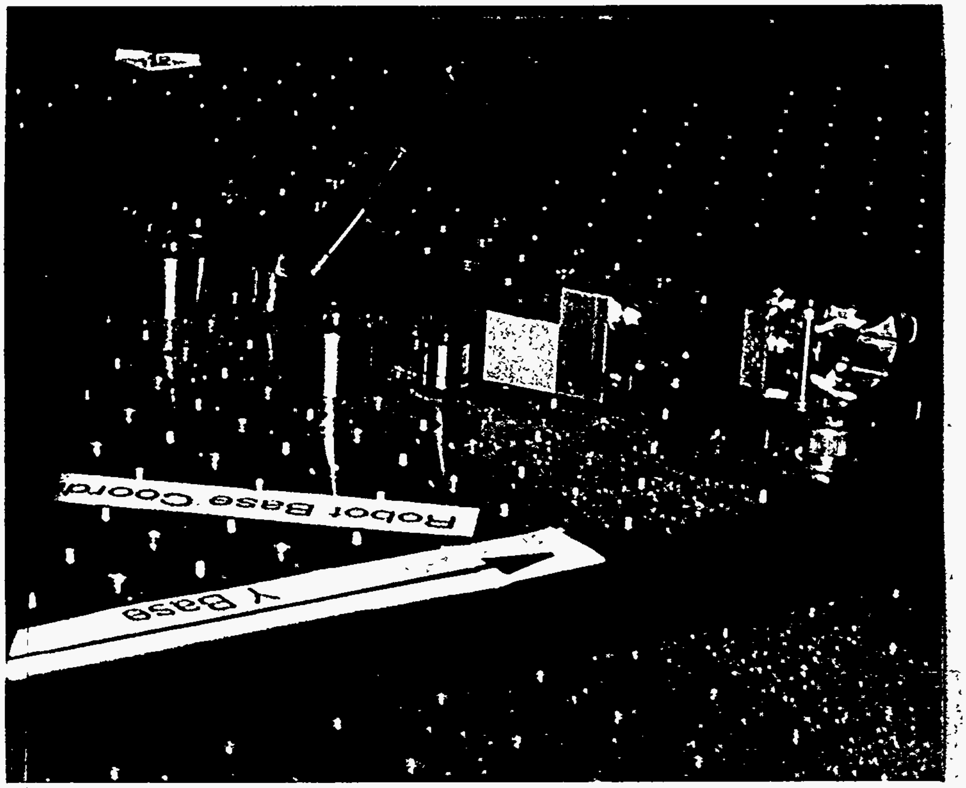

Figure 7: Testing of a Grinding Process for Robotic Edge Finishing in SNL Workcell

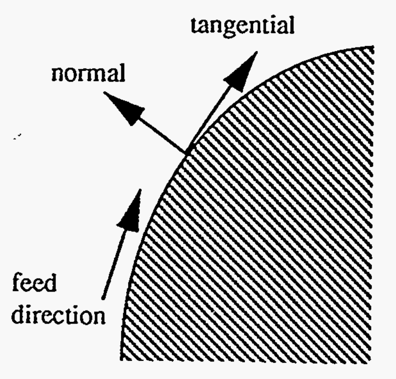

Figure 8: Defininition of Normal and Tangential Directions

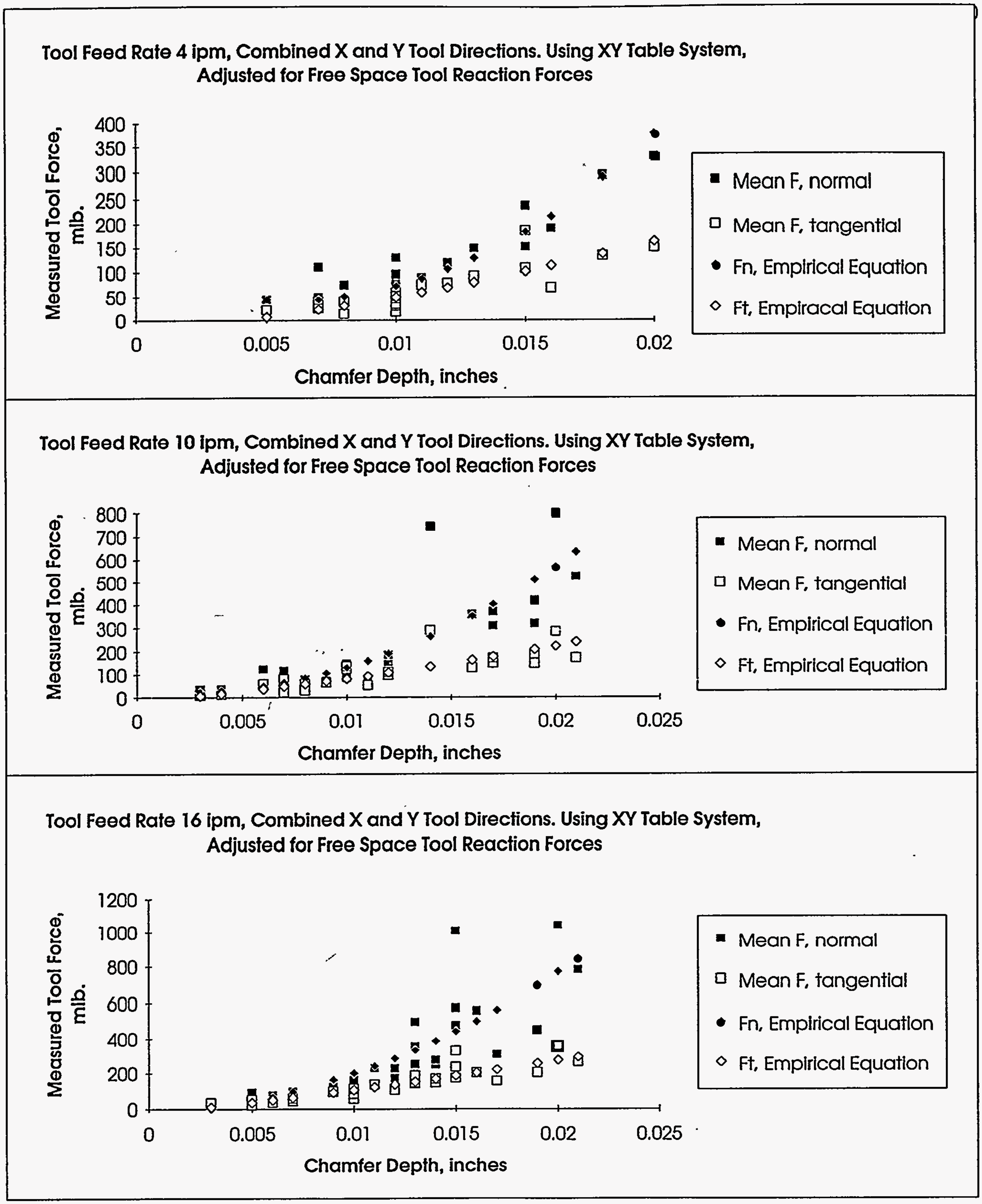

Figure 9: Mean Tool Forces Measured For Experiments On XYZ-Table And Empirical Model Resultant Curves

analysis of the data[2]. The second order empirical model agrees very well with the data, but the results pointed out the need for the bounding functions. The variability of the data appears to increase exponentially as the feedrate and tool force are increased; so much so that a process model is inaccurate at the highest feeds and force levels. The bounding function is designed to keep the system from operating in these unpredictable regions.

The first process that will be characterized in the robotic workcell is a grinding process using an 80/100 grit diamond grinding pin rotating at 35,000 rpm. The material that is being finished in the first series of tests is 304L Corrosion Resistant Steel (CRS). This material was chosen since it is very common in Sandia-designed components. Figure 10 shows a plot of the raw data[2] from the force sensor during one of the test runs on a test coupon. A separate empirical model will be needed for each material and process that is included in the database. Each empirical model needs a minimum of 28 test runs to calculate the coefficients described above and have a statistically significant number of replicates (repeated data points). Replicates are used to calculate a pooled standard deviation that provides some measure of the process variability. A 4-level, 2-variable experiment design is being used for the first process characterization that requires 52 test runs.

Additional factors can be included in the empirical model, such as tool speed or material hardness. The increased number of factors would increase the test runs required for complete characterization of the process and completion of the regression analysis. The advantage of including more factors in the empirical model is a reduction in the size of the database required for the system. For now, only feedrate and tool force will be considered to reduce the complexity of the empirical models and keep the project in-line with the original goal statement: produce a prototype that demonstrates all of the capabilities that an agile system should possess on a subset of the possible processes.

2.5 Path Planning

The purpose of this module is to allow the finishing process tool path to be verified in a virtual workcell. The path planner will provide visual verification of the tool path by the operator, indicate collisions between the robot and workcell objects, indicate problems with the tool path caused by the robot's kinematic constraints, and modify the path to avoid indicated problems. The output from this module is 10-channel hyperpoints that can be executed by the finishing system.

There are many commercial packages that would allow animation and visualization of a workcell, but our goal is to keep all modules running under the Pro Series of software. The commercial robot workcell design and simulation packages are general-purpose, relatively expensive, and usually require re-modeling of the parts using the vendor's solid model format or translation into their model format. The development team decided to implement the animation and visualization under Pro/ENGINEER to keep the hardware and software investment requirements for the system under control, limit the interface problems that can occur when translating solid models from one package to another, and limit the number of software packages with which an operator needs to be familiar to use the finishing system.

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[2]Definition: the tool X axis is in the direction of feed, the Tool Z axis is perpendicular to the cutting surface of the tool pointing into the part, the Y axis is orthogonal to the other two in a right-handed coordinate system..

A model of the Adept finishing workcell has been created using Pro/ENGINEER. Figure 11 shows the workcell model and the path planning menu that was generated using Pro/DEVELOP. The robot's kinematics have been defined and added to the model to allow animation of the robot. As work progresses, we will have the capability to load a part-fixture assembly into the workcell, load the hyperpoints defining the finishing process, and then execute the process in the virtual workcell. The system will calculate interferences, flag collisions, identify motion through singularities and configuration flips, and provide the operator with visual verification of the process.

The path planner will attempt to find safe paths by perturbing the tool orientation until a path around the singularity or configuration flip is found. The tool will be displaced by an incremental angle about the tool Y axis[3] by ever increasing amounts until a successful orientation is found or pre-set angular limits are exceeded. The required orientation changes will be added to the process hyperpoints. If the angular tool limits are exceeded, the path planner will suggest a re-location of the part within the workcell. Additional path hyperpoints may be determined by interpolation and added to the process definition to force the robot to maintain a configuration while the tool is in contact with the part. The coding for these portions of the path planner are in progress at the time of this writing.

2.6 Real-time Process Control

This is the last module in the system. This module receives the hyperpoint information that describes the process and then executes it to finish the part. The real-time process controller has two control loops (see Figure 12). The inner loop utilizes a variation of the hybrid position-force control system described in Craig[1,13]. Using this scheme, the control errors are resolved into the tool coordinate frame[3]. The system uses a position servo along two of the tool axes. A force is measured along the final axis, a force error is computed, and a gain function is used to generate a position error signal to feed back into this axis' servo loop.

A hybrid force-position control loop has been implemented in the robot workcell. This hybrid control loop maintains the force exerted on the part normal to the tool cutting surface at the setpoints specified in the incoming hyperpoints. This control scheme is being used in the robotic system for the initial process characterization studies. An alternate hybrid control loop has been implemented on the XYZ table test bed. The test bed control system uses a control law that modifies the tool feedrate to maintain a tangential tool force setpoint. Each (of these control loops) modifies the tool trajectory based on information received from a wrist mounted force sensor.

Each (of these hybrid methods) has some advantages. The normal force control scheme is less sensitive to part-model registration errors (tolerance, fixture misalignment, etc.) and works reasonably well on parts that have uniform, predictable burrs. However, if the burr size is not consistent, the tool will ride up and over a large burr and will leave an edge with a chamfered

[3]Definition: the tool X axis is in the direction of feed, the Tool Z axis is perpendicular to the cutting surface of the tool pointing into the part, the Y axis is orthogonal to the other two in a right-handed coordinate system.

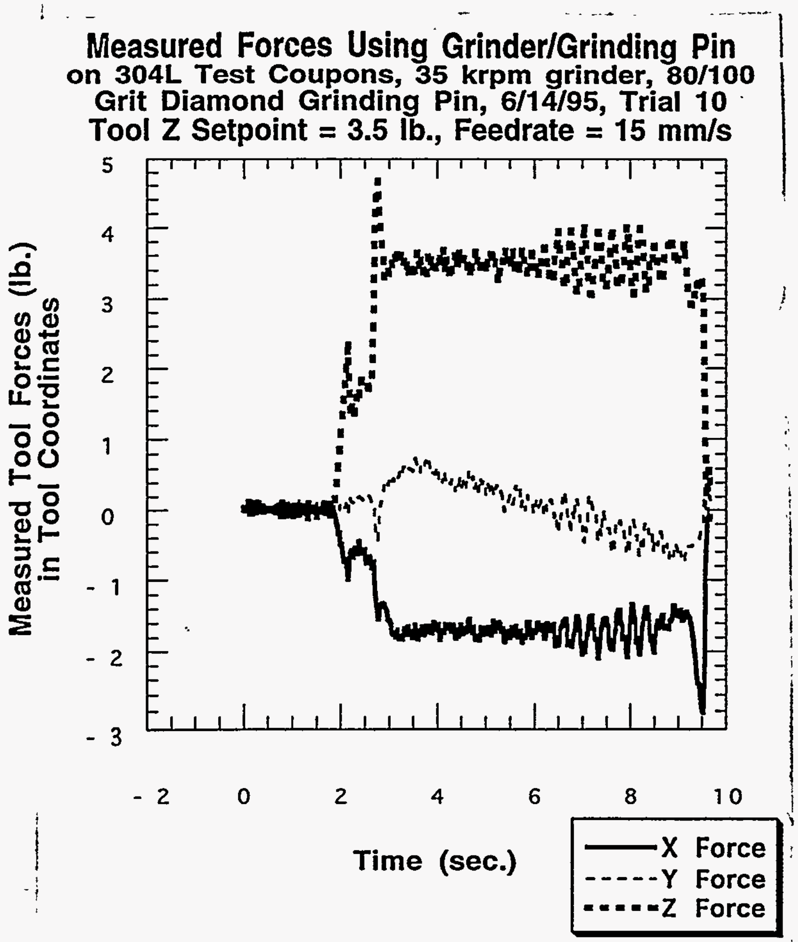

Figure 10: Plots of Raw Force Data Taken to Characterize Grinding Process

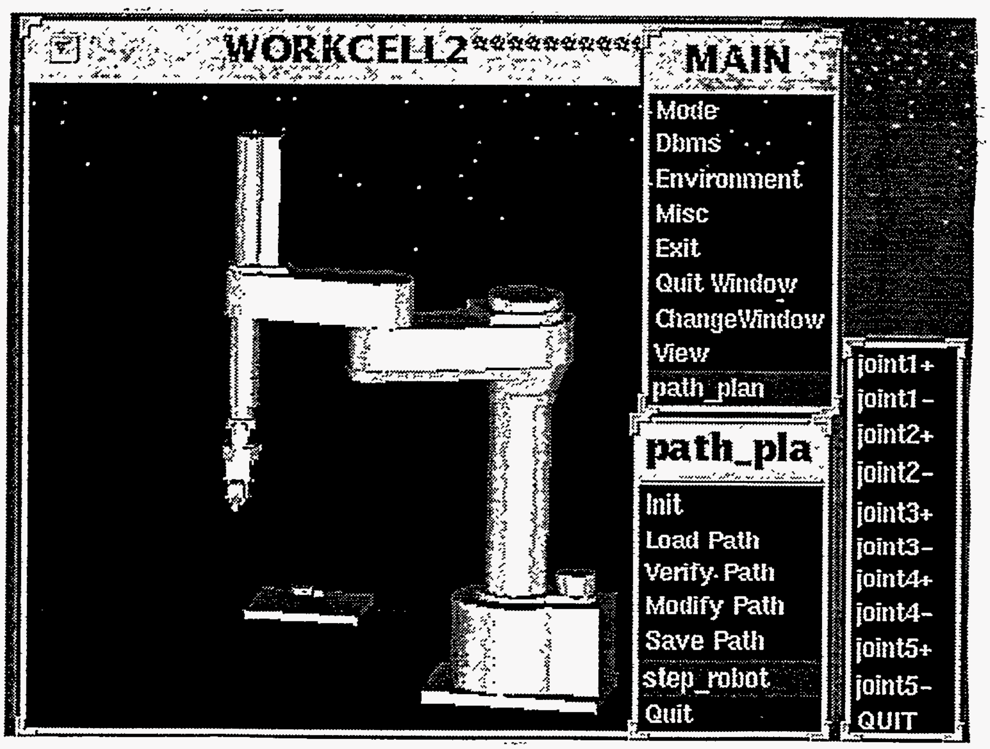

Figure 11: Workcell Model and Path Planning Menus Created for Edge Finishing

burr. The feedrate-tangential force control scheme is less sensitive to large non-uniform burrs. The controller reduces the tool feedrate as the tool machines through large burrs and increases the feedrate where the burrs are light. The downside to the feedrate-force controller is that it is more sensitive to registration errors than the normal force controller.

The outer control loop is intended to address the shortcomings of each of the hybrid force controllers. This system is currently under development. The outer loop will use a knowledge based control system and fuzzy reasoning to make adjustments to the processes, as needed. The outer loop will adjust the CAD model-work piece registration, discern and act on anomalies in force sensor output (such as might indicate tool chatter, large unpredicted burrs, etc.), and modify the force setpoint to react to sensed conditions. Eventually, the outer loop will have the capability to modify the process to perform secondary passes on an edge where a large burr is sensed and to look ahead in the tool path definition to find high bandwidth features where the tool feed/force pair needs to be modified to avoid tool gouging. Testing was taking place at the time this paper was written to identify the characteristics of the tool force signatures and identify features that indicate anomalies in the process. Once the anomalies are identified, fuzzy rules will be written to detect the anomalies and to modify the process appropriately.

3.0 Future Direction for Automated Finishing at Sandia

This paper has discussed the on-going work and planned research and development at Sandia National Laboratories for an agile automated edge finishing system. Sandia has defined a system architecture and identified technologies that are needed for an agile finishing system. The project goals and tasks have been defined to develop a prototype finishing system that demonstrates all of the capabilities required on a sub-set of possible finishing processes. Sandia is currently running tests to characterize the first process to be entered in the process planning database; developing a Pro/MANUFACTURING interface to Burr Expert software developed by the University of California-Berkeley; developing a workcell model and path planning software module for edge-finishing; investigating options for through-the-arm hybrid-position force control at the lowest level in the control system; and developing a two-level hybrid fuzzy-classical control system for process execution and modification. Research and development on each of these enabling technologies continues to gain momentum as the project progresses.

The prototype system will serve as a model for systems that will be incorporated into flexible production lines designed to meet DOE's future production needs. At the time this paper was written, the project was approximately 25% complete. The agile finishing system will be incorporated into one of Sandia's pilot manufacturing systems after this project is completed to test its capabilities in a more production-like environment and identify additional capabilities that are needed for the system. The final goal of this development effort is to replace manual finishing processes with a new class of agile edge finishing systems, designed to operate in the highly variable production environment that is projected for Sandia-designed products.

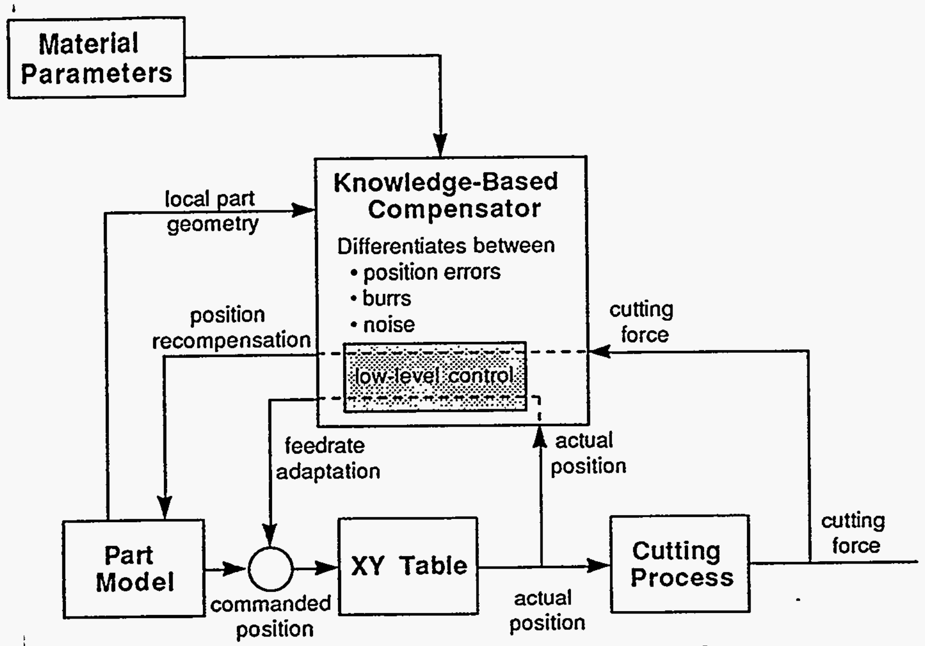

Figure 12: Low-Level Control System Block Diagram

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