Final Project Report

**Staff Exchange with
Freeborn Tool Company**

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September 1994

Prepared for
U.S. Department of Energy
under contract DE-AC06-76RLO 1830

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Final Project Report Staff Exchange with Freeborn Tool Company

Staff exchanges, such as the one described in this report, are intended to facilitate communication and collaboration among scientists and engineers at Department of Energy (DOE) laboratories, U.S. industry, and academia. Funding support for these exchanges is provided by the DOE, Office of Energy Research, Laboratory Technology Transfer Program. Funding levels for each exchange typically range from \$20,000 to \$40,000. The exchanges offer the opportunity for the laboratories to transfer technology and expertise to industry, gain a perspective on industry's problems, and develop the basis for further cooperative efforts through Cooperative Research and Development Agreements (CRADAs) or other mechanisms.

Information in this report on the staff exchange of Pacific Northwest Laboratory (PNL) staff with Freeborn Tool Company includes the purpose and objectives, a summary of activities, significant accomplishments, significant problems, industry benefits realized, recommended follow-on work and potential benefits expected from that work.

Purpose/Objective

The objectives of this staff exchange activity were as follows:

- enable PNL staff to learn and understand the problems, issues, constraints, and practices associated with successfully grinding shaper/cutter tool shapes
- enable Freeborn Tool Company to learn of the optical, computer programming, automated control, and machine design technologies available at PNL which could be beneficially used in development of an automated tool profile grinding machine
- complete a preliminary design of an automated tool profile grinding machine based upon input from both Freeborn Tool Company and PNL. The design would include, to the extent possible, detailed mechanical design, electrical/electronic schematics, specification of optical components and an outline of the software program(s) required for machine control. Freeborn Tool Company would complete the preliminary mechanical design.

Summary of Activities Performed

The exchange consisted of a series of short visits, both by PNL staff to Freeborn Tool and by Freeborn Tool staff to PNL. The series of visits extended over many months which enabled both Freeborn Tool and PNL to gain knowledge and to apply that knowledge to conceptual development and design. In this instance, that approach worked very well.

The exchange began in the first quarter, FY 1993. Over the following sixteen months, Mr. Rasmussen, PNL, made numerous visits to Freeborn's production facility in Spokane, Washington. During each of these visits, technical issues regarding automated tool grinding were discussed. Discussions ranged from mechanical design to computer control. In every case, the discussions were directed toward eventual development of such a machine for use by Freeborn in their production facility.

On several occasions, Freeborn staff visited PNL. These visits enabled interaction with additional PNL staff who could contribute expert technical input in various areas of specialization such as the application of servos to machine control, use of optical devices to determine the grinding wheel profile, and computer programming.

During early meetings, PNL staff had the opportunity to examine Freeborn's manufacturing processes in detail. This led to an in-depth understanding of the critical portions of the process. In addition, PNL staff, based on extensive prior experience, outlined the steps normally needed in successful development and deployment of new machines and devices. PNL staff also described the capabilities a newly developed grinding machine might have based upon existing, proven technology. PNL staff also presented a specific mechanical arrangement, which was the subject of an earlier invention disclosure, which potentially simplified machine control algorithms.

Based upon these initial discussions, Freeborn and PNL staff reached agreement on 1) general prototype machine configuration, 2) the overall machine development process to be followed, and 3) the areas of responsibility for both Freeborn and PNL during the continuing staff exchange. An important part of these early meetings was discussion designed to limit the expectations for the first prototype automated grinding machine. It is easy for enthusiastic individuals, regardless of affiliation, to become optimistic about the potential capabilities new technology offers. It is important when developing machines and devices to limit capabilities of initial prototypes to those that can be readily achieved using effective, concerted effort; then build on the technology demonstrated when developing subsequent prototypes.

As a consequence of the early meetings, Freeborn Tool started initial mechanical design of a prototype grinding machine. The machine would be computer controlled using a CAD drawing file of the desired cut shape (the shape the cutter would eventually make in the wood) as input. It would use an optical system to measure the edge profile of the grinding wheel and correct the machine's motions to allow for grinding wheel wear. The first machine would grind cutter blades as opposed to complete, brazed cutter assemblies. Freeborn envisions a large, future market for cutter heads with mechanically attached cutter blades (as opposed to blades attached by brazing). The prototype machine's ability to grind such blades represents a capability they do not have now.

During the remaining several months, Freeborn completed an initial prototype mechanical design. During Freeborn's design effort, PNL staff contributed in-depth information on optical methods and components needed to measure the grinding wheel, the preferred servo control motors and associated mechanical and electrical components, interfaces to the control computer, control program outlines and algorithms, and overall mechanical arrangement. Following completion of the initial design, PNL staff reviewed the design and provided comments targeted at making the machine more effective or easier to fabricate.

When the staff exchange concluded at the end of first quarter, FY 1994, Freeborn Tool had nearly completed final first prototype design and had ordered, and received, many of the stock components needed for the prototype. PNL staff had reviewed, and provided significant comment on, two mechanical design iterations. PNL had also provided specific recommendations on servo systems, optical component, and interface hardware, and outlined the computer software programs needed for machine control. PNL had also provided electrical schematics showing interconnections between the control computer, servo drivers, and the machine. Examples of the schematics are provided in Appendix A. An example of the software control algorithm is presented in Appendix B.

Significant Accomplishments

The staff exchange has resulted in Freeborn Tool personnel gaining a better understanding of how their production operation can benefit via development and implementation of fully automated grinding machines. They have also gained knowledge on the mechanical, electronic, and control methods needed to make such machines operational. PNL staff, as a result of the staff exchange, have improved their insight into production methods used when grinding shaper tools and now appreciate the problems that need to be addressed.

As a direct result of visits by PNL staff, Freeborn Tool initiated conceptual design of a proof-of-concept prototype automated grinding machine. This initial design has been completed and was forwarded to PNL for review. PNL staff reviewed the design and suggested changes. In addition, PNL staff provided mechanical, electronic, and control input to the design. The initial design and comments from the design review formed the basis for a detailed design from which a proof-of-concept prototype can be built and tested.

A follow-on Cooperative Research and Development Agreement (CRADA) between Freeborn Tool Company and PNL has been finalized. Under this two-year agreement, a proof-of-concept prototype grinding machine will be built and tested. Based on information gained during this first step, a production prototype machine will be built and tested and subsequently installed in Freeborn Tool's production line for further evaluation and testing in a production environment.

Significant Problems

No significant problems occurred during the staff exchange. Freeborn Tool management has enthusiastically supported development of an automated grinding machine. A competent Freeborn Tool Company engineer was assigned to complete the mechanical design and was provided the resources necessary to perform the job effectively. Two minor problems were encountered. First, the engineer initially assigned by Freeborn Tool to the project left the company a short time after the start of the exchange. Second, the engineer subsequently assigned to the project also has production responsibilities in the company. In a small, production-based company, production comes first and that has limited the amount of time the engineer could apply to this project. These two problems have extended the time needed to complete the staff exchange, but probably enhanced the exchange of technology between Freeborn Tool and PNL.

Industry Benefits Realized

Freeborn Tool Company manufactures more than half of the wood shaper tools made in this country. They market the tools under both their label and the label of others. Their tool grinding machines, while able to produce a quality product, are based on technology that is at least 20 years old and require significant amounts of manual operations by skilled operators. The machines also have limitations on the tools they can produce. The staff exchange and follow-on CRADA will result in development of automated grinding machines. It is anticipated that these machines will have the capability to make a broader range of shaper cutters, including cutters not economically feasible with present machines; further improve the quality of tools produced; decrease the man-power required to produce the tools; and make this small segment of the U.S. machine tool industry much more competitive with foreign manufacturers.

Recommended Follow-On Work

As discussed previously, the staff exchange has led to a CRADA between Freeborn Tool Company and PNL. It is expected that completion of the CRADA will result in an automated grinding machine being available for use in production. Other parts of the shaper cutter production process, as practiced in the U.S., are also labor intensive and can potentially be improved by application of currently available technology. These areas will be explored, but in-depth investigation of candidate areas will be delayed so that Freeborn Tool's current effort is not diluted. At present, available staff and resources at Freeborn Tool will be devoted to successful automated grinding machine development.

Potential Benefits from Pursuing Follow-On Work

The follow-on CRADA, which has been executed by all parties, will result in the development of an automated production grinding machine. The machine will initially be employed to manufacture replaceable bits for shaper cutters. At present, replaceable bits are manufactured almost entirely in Europe. Currently used U.S. grinding machines are designed to produce cutters with brazed tips and are not readily adapted to grinding replaceable bits. Successful development of the planned automated grinding machine will provide the U.S. shaper tool industry with a capability not available elsewhere and will make that industry very competitive internationally as well as domestically.

The grinding machine can also be modified slightly to grind conventional cutters with brazed tips. Used for this purpose, the machine will decrease the labor required to produce a cutter while improving product quality. It is anticipated that additional production machines will be built both for this purpose and expanded production of replaceable bits.

It is not anticipated that the developed grinding machines will be manufactured for export. Rather, they will be used by the U.S. shaper tool industry to manufacture cutter bits for use domestically and for export in this highly competitive market. Successful machine development should help move the U.S. shaper tool manufacturers toward a position of world leadership in this small segment of the machine tool industry.

Appendix A

Electrical Schematics for Automated Grinding Machine and Control System

MACHINE CONTROL, EXTERNAL I/O, and MANUAL CONTROL

The drawing referenced by this description is a ladder logic wiring diagram showing the connections, the switching logic, and the connections to the external I/O to interface to the computer control software.

The Main Power switch turns on 120 VAC to the entire cutter grinding system by energizing a contactor. There are individual On/Off component power switches for the PC computer - monitor, the camera measurement system, and the DR 500 Driver for the servo motors, which control individual contactors.

The E-STOP switch is designed in the electrical connections to remove 120 VAC from most parts of the system. The computer, camera measurement system, and the DR 500 Driver will remain powered. The grinding motor, coolant solenoids, and gate solenoids will be de-energized and return to the nominal state. A set of contacts on the E-Stop Relay are wired into the E-Stop input on the DR 500 Driver. This will just stop the servo motion, but keep the servo powered so that the present position would be maintained and none of the axes coast or drift due to weight. A review of the DR 500 Driver documentation to determine if the E-Stop input provided directly into the Driver circuitry allows this type of operation was inconclusive. I've only showed one E-STOP switch, but several can be wired in series to provide the E-Stop function at various locations.

The STOP MOTION switch and the Interlock switches are intended to stop the servo motors from moving any axes, shut off the coolant flow, and shut off the grinding motor; but would not shut down any other power. This is a stop that is less severe than an E-Stop.

The HALT switch is intended as an input to the computer software program. The HALT function would stop the motion of the servo motors under software control. As long as the Halt switch is pushed, the control program would stop moving the servo motors, and when the Halt is released the motion would resume at the point it was halted. The HALT switch would only be active in the AUTO mode.

The AUTO/MANUAL switch is used to switch between two different modes of operation for the cutter grinding system. In AUTO mode, the control software has total control of the grinding system. The operator will be prompted to do several tasks, and respond by pushing the START switch to acknowledge the completion of the task. The logic for AUTO operation is to have all manual operational components disabled when in the AUTO mode.

In the MANUAL mode, separate control switches are operational for the grinding motor, coolant flow control, and the gates for the camera based measurement components. After switching to the MANUAL mode, the MANUAL ENABLE switch must be pushed to gain access to the MANUAL control functions. Also manual control of each of the four motor axes is available. This control will operate through control software. A direction switch input for each axes is used to determine the direction of movement. A jog pushbutton, one for each of the four axes, moves the corresponding servo motor at slow speed as long as the

pushbutton is held engaged. The jog motion is performed under control software so that positional data for each axes is maintained and relative movement data and absolute position data from Home can be obtained.

The external I/O interface to the control software is through OPTO 22 modules. The OPTO 22 board is connected via ribbon cable to the Aerotech control board in the computer system. The OPTO modules are identified as OAC5A for outputs, and IAC5 for inputs. The following # is a physical location in the Opto interface module, and the numbers in gray boxes are terminal strip designations for wire connections.

120 VAC - MAIN INPUT

460 VAC

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Item - Description	Quantity	Part Number	Reference
Contactor - 30 A 120 VAC Power	1	Square D 8910DP31V02	Newark # 50F42
Fuse 30 Amp	1	Littel Fuse FLN - R - 30 9/16 x 2	Newark # 81F21
Fuse Holder 30 Amp - 1 Pole	1	Marathon Fuseholder F30A1B	Newark # 96F52
Contactor - 20 Amp Component Power	4	Square D 8910DP11V02	Newark # 50F42
Control Relays SM/I, ESR, A/M, and MER	7	Potter & Brumfield KHU17A12 [4PDT]	Newark # 62F30
Relay Socket	7	Potter & Brumfield 27E894	Newark # 46F31
3 - Pole Contactor	1	Square D 8910DPA13V02	Newark # 50F42
Auxiliary Contacts	2	Square D 9999D11	Newark # 50F42
Fuse 2 Amp	3	Littel Fuse FLQ - 2	Newark # 81F22
Fuse Block	1	Littel Fuse L60030M - 3SQ [3 - Pole]	Newark # 90F8
Delay Relay - DPDT [0.1 - 5 sec] START	1	Potter & Brumfield CB - 1011B79 [AC Type]	Newark # 90F1
Relay Socket - 8 pin	1	Potter & Brumfield 27E891	Newark # 46F31

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Appendix B

Software Algorithm Outline for Automated Grinding Machine

Freeborn Tool Grinder Software Outline

1. Offline program to convert .dxf file (from AutoCAD) to tip profile data.

Inputs:

.DXF file of desired INVERSE wood shape OR tip shape.

D_t = tool diameter

Φ_{hook} = hook angle

y_{offset} = offset of tip from "x" axis of tool

$\Phi_{clearance}$ = Clearance angle this can vary along the profile, and horizontal and vertical components can be given separately

Step Size - for digitizing profile

Outputs:

n_{points}

$n_{segments}$

change_pointers[i], $i = 1, n_{segments}$

for $i = 1, n_{points}$

$x_t(i), y_t(i), \Phi_{tan}(i), \Phi_{cl_vert}(i), \Phi_{tot_horiz}(i)$

Step 0

Read in .DXF file and extract the desired profile (lines and arcs).

Read in Φ_{hook}, D_t .

Step 1

Verify that profile y dimensions are consistent with input parameters

find y_{smax} for input profile

if (inverse wood shape)

$$d = D_t \sin(\Phi_{hook}) / 2$$

else (tool shape input)

$$d = 0$$

$$\alpha = \tan^{-1} \left[\frac{y_{offset}}{d} \right]$$

$$y_{s_offset} = \sqrt{y_{offset}^2 + d^2}$$

$$offset = D_t/2 - y_{offset} - y_{smax}$$

if (offset)

bump y values for lines by offset

bump y values for arc centers by offset

step 1.5 chk for closure

Step 2

Generate a rough cut profile with δ excess material

replace lines with a parallel line a distance δ above or **inside** the given line

increase radius of convex arcs by δ

decrease radius of concave arcs by δ
re-connect the segments, mindful of corners, possible "lost" segments

Step 3

Convert profiles (lines and arcs) to continuous digitized profiles WITH TANGENTS.
step size = STEP_SIZE (likely .001")

Note: Identify connection points between segments.

Step 4

Convert inverse wood profile to tip profile.

for entire profile:

if (inverse wood shape was input)

$$y_t(i) = \sqrt{[y_{s_offset} + y_s(i)]^2 - d^2} - y_{offset}$$

else (tool shape was input)

$$y_t(i) = y_s(i) - y_{offset}$$

How does this affect the tangent??

x_t remains unchanged

Note: Step size is distorted slightly by this operation.

Step 5 Can we skip this??

Compute the tangent for each point

$$\delta y = y_t(i+1) - y_t(i) \text{ (last point: } \delta y = y_t(i) - y_t(i-1))$$

$$\delta x = x_t(i+1) - x_t(i) \text{ (last point: } \delta x = x_t(i) - x_t(i-1))$$

$$\Phi_{tan}(i) = \text{ATAN2}(\delta y, \delta x)$$

Step 4

Compute clearance angle components

$$\Phi_{cl_vert}(i) = \Phi_{cl}(i) \sin(\Phi_{tan}(i)) = \text{skew angle (about +y axis)}$$

$$\Phi_{cl_horiz}(i) = \Phi_{cl}(i) \cos(\Phi_{tan}(i))$$

$$\Phi_{zero_clearance}(i) = \tan^{-1}[d/(y_t(i) + y_{offset})]$$

$$\Phi_{tot_horiz}(i) = \Phi_{cl_horiz}(i) + \Phi_{zero_clearance}(i)$$

Step 5

Count the number of segments that the profile must be broken into to insure that grinding always takes place toward the tip. When the tangent is negative, grinding is in the +x direction. When the tangent is positive, grinding is in the -x direction. When the tangent is zero, grinding can be in either direction, with the direction chosen to minimize the number of

segments. Reverse the order of the segments where the grinding direction is reversed. Also, add a segment boundary at corners where the tangent decreases to avoid grinding off the corner.

Check Don's algorithm

```

n_segments = 0
tangent_direction = tangent of first point
for (i=0; i<n_points; i++)
    if ((( $\Phi_{tan}(i) \leq 0$ ) AND (tangent_direction > 0))
        OR
        (( $\Phi_{tan}(i) > 0$ ) AND (tangent_direction < 0))) (indicates when tangent changes sign)
        OR
        (this point is a corner and the tangent is decreases)
            change_pointers [n_segments] = i
            n_segments += 1
            tangent_direction = sign ( $\Phi_{tan}(i)$ ) (-1 if  $\Phi_{tan}(i) = 0$ )

```

now reverse the order on the segments in which grinding is left to right

```

for (i = 0, n_segments)
{
    if ( $\Phi_{tan}[change\_pointers[i]] > 0$ )
        start_point = change_pointers [i]
        end_point = change_pointers [i+1] - 1
        reverse_order (start_point, end_point, buffer) buffer =  $x_t, y_t, \Phi_{tan}, \Phi_{cl\_vert}, \Phi_{tot\_horiz}$ 
}
n_segments += 1

```

Step 6

Write data to disk

```

n_points
n_segments
change_pointers[i], i = 1, n_segments
for i = 1, n_points
     $x_t(i), y_t(i), \Phi_{tan}(i), \Phi_{cl\_vert}(i), \Phi_{tot\_horiz}(i)$ 

```

Variables

D_t = tool diameter
 Φ_{hook} = hook angle
 $d = D_t \sin(\Phi)$ = offset of tip from tool centerline
 y_{smax} = maximum y dimension of inverse of cut wood shape
 y_{tmax} = maximum y dimension of tip profile
 $y_{s_offset} = D_t/2 - y_{smax}$ = difference between the tool diameter and maximum height of input wood shape

$n_{segments}$ = number of segments that the profile must be broken into to insure that grinding always takes place toward the tip.

n_{points} = total number of points that the tip profile is divided into

change_pointers [i] = vector of profile point numbers at which the grinding direction changes

tangent_direction = 1 or -1 - keeps track of sign of the tangent

$y_{offset} = \sqrt{(D_t/2)^2 - d^2} - y_{t,max}$ = offset of the base of the tip from the plane ($y=0$) of the cutting tool

$y_t(i) = \sqrt{[F + y_s(i)]^2 - d^2} - y_{offset}$ = y dimension of tip profile point i

$x_t(i)$ = y dimension of tip profile point i

$\Phi_{clearance}$ = Clearance angle (can vary along the profile)

$\Phi_{cl_vert}(i) = \Phi_{cl}(i) \sin(\Phi_{tan}(i))$ = skew angle (about +y axis) = vertical component of Φ_{cl}

$\Phi_{cl_horiz}(i) = \Phi_{cl}(i) \cos(\Phi_{tan}(i))$ = horizontal component of Φ_{cl}

$\Phi_{zero_clearance}(i) = \tan^{-1}[d/(y_t(i) + y_{offset})]$ = zero clearance horizontal undercut angle

$\Phi_{tot_horiz}(i) = \Phi_{cl_horiz}(i) + \Phi_{zero_clearance}(i)$ = total horizontal undercut angle

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