A High Performance
Embedded Machine Tool Controller

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ABSTRACT

A Diamond Turning Machine (DTM) can fabricate components with extremely high precision and high quality surface finish characteristics. Existing commercial controllers are limited in their ability to support high performance machining and related advanced control algorithms. Evolving enhancements to the functional capability and control algorithms of a DTM require increased performance and flexibility from the computer system controlling it. To provide this capability the Precision Engineering Center at North Carolina State University has developed and implemented a high performance control system for such a machine tool. The control system is based on a heterogeneous hierarchical multiprocessor computer architecture. This provides the capacity to apply advanced control concepts to the DTM, resulting in improved precision and quality of machined parts. Additionally, the ability to machine non-rotationally symmetric components has been made possible by application of multiprocessor capability.

Keywords:
computer control, multiprocessing systems, precision machining, real-time computer systems
1. INTRODUCTION

High precision machining has become increasingly important to manufacturing and the world economy. Common consumer items such as video cassette recorders and compact disk players contain components machined to tolerances which were once found only on research and military equipment. The increasing need for commercial production of high precision items has challenged precision manufacturing capabilities. In response, new technologies must be developed and advanced in order to machine more difficult materials and geometries both accurately and efficiently.

Optical manufacturing is one area which demands extremely high precision. Traditionally, optical manufacturing techniques involved a grinding process to establish the desired shape followed by a polishing process to achieve the required surface qualities. This two step process is time consuming and form accuracy is diminished in the polishing process. A Diamond Turning Machine (DTM) is an ultraprecision computer numerically controlled (CNC) lathe. The cutting tool is a highly polished single point diamond tool. The technique of machining, in a single step, optical quality surfaces on a diamond turning machine (DTM) has revolutionized the fabrication of reflective and transmissive optical components. This technique also frees the optical designer from the constraints of spherical shapes and provides a method of integrating the optical surface into the mechanical structure.

A typical DTM configuration consists of two orthogonally configured precision slideways along which the cutting tool and/or workpiece move. The workpiece is mounted to a rotating spindle. Like other turning techniques, diamond turning produces surfaces of revolution, that is surfaces which do not vary as a function of rotation. Production of surfaces which are non-rotationally symmetric (NRS) require the means to move the cutting tool in a direction normal to the plane of the surface as the workpiece rotates. Machining of NRS surfaces has been limited by the physical bandwidth of the mechanical positioning systems of existing DTMs. The Precision Engineering
Center (PEC) at North Carolina State University has developed an electronic fast tool servo (FTS) positioner which can meet the bandwidth demands of NRS machining [7].

The Precision Engineering Center's DTM is a test bed for the development of advanced machining technology. To support this research, the commercially built CNC system was removed and replaced with a custom computer control system to provide the flexibility to investigate and implement new techniques. The limitations of currently available commercial controllers are due to processor computational power and openness of the architecture. High-speed I/O is required for the large volume of data and the fast data rate necessary for machining a non-rotationally symmetric part. Current controllers are unable to generate reference positions, to calculate the control algorithms necessary for the machine axes, or to provide correction of the geometric errors within appropriate time constraints. Also, the closed nature of the hardware and software architecture of most controllers does not allow additions of new inputs or outputs or major changes in control algorithms. To solve this controller problem a Heterogeneous Hierarchical Architecture for Real-Time (H²ART) has been designed and implemented at the PEC. This is a high performance multiprocessor based computer system that provides both computational power and I/O flexibility.

2. DIAMOND TURNING MACHINE AND FAST TOOL SERVO CHARACTERISTICS

A Pneumo ASG 2500 Diamond Turning Machine at the Precision Engineering Center has been used as a testbed in the development of extended functionality and improved control algorithms. With its commercial controller, this machine is specified to provide a figure accuracy of better than 350nm across a 100mm workpiece and a finish surface roughness of 10nm Ra. This machine is configured with a rotating spindle mounted on the Z direction slide and the cutting tool mounted on the X direction slide. Figure 1 shows a plan view of the DTM illustrating axis orientation. Precise measurement of the location of the tool relative to the workpiece is critical to precision machine control. The Pneumo DTM utilizes laser interferometric measurement systems to measure the
position of the X and Z slides to a resolution of 2.5nm. For the machining of NRS parts, the rotational position of the spindle must be known as well as tool position. An optical encoder attached to the spindle generates 4096 pulses per revolution giving a resolution better than 0.1 degree (.0015 rad) of rotational position. Also depicted in Figure 1, is the FTS axis which is referred to as Z’. The FTS is a piezoelectric actuator capable of moving the cutting tool normal to the workpiece surface at a high frequency. Typical bandwidths of FTS devices are 100Hz to 2KHz and displacement ranges are .1mm to .025mm. The position of the FTS actuator is measured by a capacitance gage with resolutions ranging from 25nm to 10nm.

![Diagram of DTM / FTS Axis Orientation](image)

**Figure 1:** DTM / FTS Axis Orientation

### 3. COMPUTER CONTROL FOR A DIAMOND TURNING MACHINE

Commercial control systems supplied with a DTM are generally standard CNC (computer numerical control) systems intended for application to a wide variety of machine tools. As such, they have limited features and capabilities needed for a high performance ultraprecision research system. These CNC controllers generally have control cycle times of 5-10ms (100-200Hz) and they incorporate a single algorithm, usually PID, for dynamic control of the machine. For development of high-precision machine control, the control system must be capable of much higher control cycle rates (1-10KHz) and have the flexibility to incorporate complex control algorithms. The computer control system must also have the capability to acquire experimental measurements...
from the machining process to assist in evaluating and refining control strategies. Both open and closed loop performance monitoring of axes response with data filtering and adjustable sample rates will provide these measurements. Data archive facilities must not interfere with the controller update cycle. This data archiving capability can be utilized in the development of the machine error budget as well as control algorithms. Additionally, the ability to easily expand and modify the control system to incorporate new control algorithms and to accommodate new measurement and actuation devices is required.

3.1 DTM / FTS Control Tasks

There are three major functional elements of a control system for a DTM: user interface, reference signal generation and axis control. The user interface provides the user with the means to direct and monitor the operation of the DTM during a machining operation. The reference signal generation calculates the paths that the tool and workpiece must follow to create the desired shape. The axis control moves the tool and workpiece during machining to follow the path defined by the reference signal.

**User Interface:** Machine operation is initiated by the user through a set of keyboard commands or via menu selection. These commands include facilities for multi-step part program interpretation. DTM status is continuously displayed in real-time on a color video monitor with separate windows reserved for axes position and velocity updates, error messages, part program status information, and user command scrolling. Extensive command line editing, history, and recall functions are available. These single line editing functions allow sequences of commands to be easily repeated with a minimum of keystrokes by the user. They also allow the user to view old commands that have scrolled off the screen.

The DTM controller software provides a foundation for the further development of control algorithms. Several control schemes other than PID have been implemented to control the DTM
slides. These include discrete lag compensation, butterworth filtering and force feedback control. A uniform sum of products structure is used for the calculations of each control law. Switching control types requires down-loading new constants to the control law calculation procedure. Commands are available to select the control type and the gain constants independently for each axis. The axes gains can be entered at the command line or read from an input file. To aid in the system identification and controller evaluation tasks, two additional control programs are provided. One uses an input file containing an arbitrary signal as the reference input for the type of control currently selected. The other program accepts a similar input file but uses the data as the open loop output to each axis. Data recorded by these programs can be used to determine the open and closed loop response of the DTM to any input signal.

The fundamental control loop timing can also be set by the user. The range of permissible values is 0.5ms to 25ms. A probe output is also available to test the accuracy of the controller timing. A software biasing command reduces the frequency of machine adjustments to correct for drift in the digital-to-analog converters (DACs). A checkpoint/restart facility allows machine setup parameters and operator preferences to be saved and restored from disk. This allows the recovery of tool position information in the event of system failure. It also simplifies resetting the controller to its normal operating mode after completion of software or machine testing. The absolute range of axes motion can be restricted with operator commands. This provides additional security during control algorithm testing and for cutting applications that require complex fixturing (e.g., grinding).

A batch file execution feature allows long sequences of commands to be executed without the presence of an operator. This has proved useful for machine control and cutting experiments that require many iterations of the same axis motion with different parameters and for lengthy data collection activities (e.g., spindle growth tests over 36 hours). A delay feature allows tests to be
conducted after the operator has left the room, thus eliminating one significant environmental effect.

**Reference Surface Generation Algorithms:** One of the basic computational problems encountered in implementing a machine tool controller is the precise description of the desired part surface in a form appropriate for computer input. This surface description is then translated into a tool path for the target machine axes orientation. The detailed tool path is used as the reference input to the closed loop control algorithm. Any defects in this reference signal will be realized in the resulting machined surface. For the high-precision machining of complex geometries, the number of components (i.e., part program blocks) in the desired tool path may be prohibitively large for off-line calculation and on-line storage while machining. This naturally leads to the notion of *on-the-fly* reference signal generation. For a FTS, the reference position is itself a function of two independent feedback inputs and cannot be calculated off-line.

All symmetric reference surfaces (linear and non-linear) can be generated using a parametric representation of the appropriate mathematical equations. The reference signal generation algorithms for non-linear surfaces utilize parametric forms of the standard conic equations. These parametric forms have three advantages for interpolation algorithms. The specific equations chosen are optimal in that straight lines connecting the generated points will inscribe a polygon of maximal area under the desired curve. Tool correction formulas are conveniently expressed in terms of the parametric variable, which is incremented by a constant on each iteration of the algorithm. This leads to simplification of the tool correction formula. The fundamental, unsimplified form of the parametric equations also allows reference signal generation to be performed independently for each axis.

**FTS Reference Surface Generation:** The machining of non-rotationally symmetric workpieces using the fast tool servo system presents a significant computational load which
requires the use of a dedicated processor to control the tool servo. One application for this capability is the machining of off-axis conic sections. These can be segments of a mirror too large to machine as a single element.

The decomposition of the general aspheric optics equation into rotationally symmetric and non-rotationally symmetric components suitable for on-axis FTS machining of off-axis conic segments has been described [4,5]. This solution minimizes the range of motion required of the FTS by tilting the workpiece. The best fit asphere can be generated off-line as a sequence of cords. The number of cords can be adjusted to obtain any accuracy required in the asphere approximation. A high-speed axes control processor could also be used to generate the asphere on-the-fly.

The derivation of the surface equations and the method of dividing the total surface into symmetric and non-symmetric components is discussed below. The general equation of an optical surface of revolution about the Z axis can be written as [6]

\[
z = \frac{cs^2}{1 + \sqrt{1 - (k+1) c^2 s^2}} + a_1 s^4 + a_2 s^6 + a_3 s^8 + a_4 s^{10} + \ldots
\]

(1)

where

\[s^2 = x^2 + y^2 \text{ and } c = \frac{1}{r} = \frac{1}{\text{radius of curvature}}\]

The aspheric deformation constants (a_i) will be assumed to be zero so that the surface is a conic surface of revolution. The constant k is related to the eccentricity (e) of the conic (k = -e^2) and defines its shape.

The geometry of the off-axis segment and its orientation in the parent coordinate system is shown in Figure 2. Fabrication of a segment of this surface by on-axis machining requires three coordinate transformations (translation, rotation and transformation to a cylindrical system) to produce the equation for the surface as a function of the radius and the angle of rotation of the spindle. These transformations have been published by Gerchman [4] and the resulting equation for on-axis fabrication of a general conic surface of revolution is
\[ z = d_1 + d_2 \rho \cos(\theta) - \sqrt{d_3 + d_4 \rho \cos(\theta) + d_5 \rho^2 + d_6 \rho^2 \cos^2(\theta)} \]  \hspace{1cm} (2)

**Figure 2.** Geometry of Off-Axis Segment in Framework of Parent Conic [4].

Equation (2) gives the value of \( Z \) as a function of the radius from the spindle axis (\( \rho \)) and the rotational angle (\( \theta \)) of the spindle. It consists of both a rotationally symmetric component and a non-rotationally symmetric component. The constants (\( d_i \)) in Equation (2) depend upon the conic constant, \( k \), the off-axis translation parameters (\( x_0, z_0 \)) and the angle of tilt (\( \alpha \)) of the surface. The initial selection of the tilt angle is the tangent angle of the parent conic at the center of the segment. An iterative approximation technique is used to find the angle that minimizes the excursion of the fast tool servo. Once an acceptable value for \( \alpha \) is determined the two components of the surface shape can be written as variations of Equation (2). The rotationally symmetric part will be the value of \( Z \) at \( \theta = \pi/2 \), and the non-rotationally symmetric part will be the difference between the value of \( Z \) from Equation (2) and the rotationally symmetric part.
The evaluation of Equation (2) using 32-bit floating-point arithmetic may give incorrect results due to the subtraction of two large but nearly equal quantities. A further simplification is possible that solves this loss of precision problem. It also reduces the evaluation time of the function by approximating the square root operation with a polynomial expansion. The final simplified form of Equation (2) becomes [3]

\[ z = d_2\rho \cos(\theta) - d_1 \left[ \frac{1}{2} E - \frac{1}{8} E^2 + \frac{1}{16} E^3 - \frac{5}{128} E^4 + \ldots \right] \]

(3)

where \( E \) is given by

\[ E = \frac{d_4}{d_3} \rho \cos(\theta) + \frac{d_5}{d_3} \rho^2 + \frac{d_6}{d_3} \rho^2 \cos^2(\theta) \]

(4)

Using Equations (3) and (4) the integrated FTS controller calculates the Z axis reference position (as a function of the current \( \rho \) and \( \theta \)) in real-time and subtracts the current Z axis position to obtain the small perturbation component \( Z' \). Using the actual axes positions in the reference calculation allows the FTS controller to compensate for high-frequency Z axis vibrations as well as the low-frequency positioning error of the slower DTM axes controller.

**Multi-Step Part Program Interpretation:** The complete sequence of machine axis movements required to produce a surface is processed by the part program translator before execution. Constraint testing and tool path verification operations are performed during the translation of an ASCII part description file into an internal format suitable for interpretation. Each movement command in this file (e.g., line, arc) is converted into one or more program blocks that drive the interpretation process. The blocks contain all relevant geometric parameters as well as pointers to *block setup* and *next setpoint* functions. In this way complex and time consuming initialization operations can be performed off-line before initiating machine operation.
The resulting sequence of blocks is an internal description of the complete reference signal
generation task for the DTM axes controller.

The part program interpreter drives the machine axes along the desired toolpath by executing each
block in the sequence. Pre-initialization of parameters during the translation phase minimizes the
block transition overhead. The block setup function moves the initial block parameters from the
block data structure into runtime interpolation variables. The next setpoint function is invoked
to obtain successive axes setpoints. Additional block parameters indicate the programmed feedrate
and the number of setpoints to generate for each block.

**Feedback Axis Control:** All control laws implemented for the control of the DTM axes (e.g.,
PID, lead-lag) can be expressed as a sum of products involving previous states of the machine and
user defined gain arrays (kv and ke). Position errors (e) and velocity outputs (v) for up to eight
previous control cycles are available. The calculation of the velocity output for a single axis at time
\( t \) is given by

\[
v_t = \sum_{i=1}^{n} kv_{i-1} \times v_{t-i} + \sum_{j=0}^{m-1} ke_j \times e_{t-j} \quad \text{where } n,m \leq 8.
\]

### 3.2 Enhanced DTM Control

Improving the form accuracy and surface roughness of the machined parts is another focus of
ongoing research. Current objectives are to improve both parameters by a factor of 5. Several
techniques to achieve this goal have been investigated or are currently under investigation.
Incorporation of these into the control algorithms of the DTM require varying amounts of the
computing resource. Some of these techniques involve geometric error corrections, tool force
feedback control, spindle runout correction, and dynamic vibration control. These techniques and
the improvements yielded by their application are briefly described below. Incorporation of these
advanced control techniques require ever faster control cycle times thus requiring escalating
computational capability. The H$^2$ART system can evolve seamlessly as computational demands grow.

**Slideway Geometry Correction:** Even though the slideways of the DTM are precision machined, they are not perfectly straight or square. This results in positioning errors in both X and Z. Furthermore, spindle alignment error results in a yaw of the workpiece as the Z slide is moved. A straightness errors of ~500nm and a yaw error of up to 2000nm were measured on the PEC DTM. These errors are repeatable and can be compensated for by the axis control algorithms.

**Tool Geometry Compensation:** The motion of the tool with respect to the workpiece can be programmed to follow any prescribed path. However, for non-flat surfaces, the point of contact between the tool and the workpiece is not constant. The resulting machined surface will have a slightly different shape from that desired. In most precision machining applications the relative magnitude of this error is quite large (i.e., on the order of 1 µm). The error induced by the tool is dependent on both the programmed surface and the tool parameters (usually an ellipsoid with some surface waviness). The characterization of the tool is in fact an approximation and of course the tool wears during machining and thus its shape is dynamic. The known errors in the tool can be used to modify the reference signal so the point of contact is on the desired curve.

**Slide Vibration Control:** As with any mechanical system, there are vibrations created in the DTM during machining which may adversely affect surface finish. Control algorithms which compensate for and reduce these vibrational effects are being developed.

**Spindle Runout Compensation:** Though it runs in precision bearings, the DTM spindle exhibits both axial and radial runout. Dynamic measurement of and correction for spindle runout will require fast (~10KHz) control loops driving a two-axis FTS.
Tool Force Feedback Control: Tool forces can be dynamically measured by sensors placed on the tool holder. Research has indicated that these measurements can be used in the control algorithms to improve surface finish.

3.3 Control System Partitioning

Development of the Fast Tool Servo (FTS) enhancement for the DTM requires multiple processors to perform the required control computations. Texas Instruments TMS320C30 floating-point digital signal processors are used for all control tasks. A custom multiprocessor architecture provides a platform for maintaining the high I/O and computational throughput needed for a successful controller implementation.

When considering the partitioning of an integrated control system for multiprocessor implementation two factors must be considered. First is the logical partitioning of the tasks which make up the system. This step is generally done along functional lines. Only in situations where the computational load requires more than one processor will a single control function be split across more than one processor. After tasks are logically partitioned, the flow of data between processors must be evaluated. Since a finite amount of time is required to pass data between processors in a multiprocessor system, the design must insure that data flow capacity and latency requirements are not exceeded.

An externally acquired data value may be required for the control computation in more than one processor. Therefore, the point of acquisition of the data and its subsequent distribution to the remainder of the system must be included in the data flow analysis. In the advanced DTM controller, the critical external data is the laser position data. This information provides the reference basis for all control calculations.
3.4 DTM Control I/O Requirements

There are a variety of sensor inputs and actuator outputs required to control the DTM. Inputs consist largely of measurements of the positions of the movable elements of the DTM along with various signals indicating the machine status. Outputs drive the actuators which position the slideways and the FTS. The input/output data requirements of each of the control processes are shown in Table 1. This table reflects only the I/O data required for the existing DTM/FTS control system. Experimental measurement support as well as additional sensors and actuators require flexible I/O capabilities. Typical sensor inputs which may be incorporated in the near future include on-line tool force and spindle runout measurements.

<table>
<thead>
<tr>
<th>Process</th>
<th>Function</th>
<th>Analog</th>
<th>Digital</th>
<th>Input</th>
<th>Output</th>
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<tbody>
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<td>X and Z Laser Data</td>
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<td>FTS Controller</td>
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<td></td>
<td>Machine Functions</td>
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Table 1: DTM / FTS Process Input / Output Requirements

3.5 DTM Control System

A computer system based on a PEC developed Hierarchical Heterogeneous Architecture for Real-Time (H²ART) provides the computational power for advanced control algorithms. This architecture consists of multiple nodes each containing a node controller and one or more computational processors. To eliminate the bottleneck of having a centralized I/O facility, each computational processor has its own I/O interface. This allows the computational processors to function autonomously (except for coordinating data shared by several processors). The H²ART
architecture provides a system that is flexible and readily scalable to accommodate future system growth.

The target for an advanced control system for a DTM is to provide capability for a 2KHz control rate for X and Z axes and on the order of 10KHz for Z' (FTS) with additional computational capacity for implementation of advanced control algorithms. Control enhancements include geometric error correction and slide vibration reduction. Other functional goals include tool force feedback control, a long range fast tool servo, spindle runout correction, on-line tool wear compensation, enhanced operator interface and continuous data archiving.

The DTM/FTS control application requires multiple processors. Major decisions in the implementation of the new control system revolve around how to partition the control application and how to determine the number of control processors required. A natural partitioning of the DTM/FTS application is along functional control lines. This application has four major components: X axis control, Z axis control, FTS control, and system coordination. In the H^2ART based DTM/FTS control system, the integrated application is partitioned and distributed across four TMS320C30 control processors. Each of the major axes (X, Z) is controlled by a separate processor. FTS control utilizes a third processor dedicated to that function. The fourth processor is assigned to coordinating the other three and processing manual operator requests. The 80186 node controllers will manage acquisition of data for archiving and communications with the host system. Currently, the host computer for the system is a PC-AT. A block diagram of the DTM/FTS control system is shown in Figure 3. This system will provide the computational power necessary for supporting the next generation of control strategies for the DTM.
Figure 3: DTM / FTS Control System Configuration

### 3.6 Control System Data Flow

While laser position data constitutes the majority of time critical data which flows through the control system, there are other data which must pass through the control system to ensure correct and coordinated operations. This includes part programs, data to be archived, machine function commands, etc. The major data flow paths of the control system are shown in Figure 4.

There are two types of real-time data flows through the control system. First is real-time data used by the algorithms to calculate the control actions needed for the machining process. This data is
normally acquired by the processor needing it via its own I/O interface. One exception is laser position data which is discussed below. Second is command data which coordinates the operation of all the processors while machining a part. Examples of command data include part program information, functional coordination (start, stop, etc.), and machine control (E-stop, safety interlocks, etc.).

Figure 4: DTM / FTS Data Flow

The reading of position data from the laser measuring system is performed under computer control. Since it is not practical to have multiple computers trying to control the same device, the read of the laser data must be managed by one of the system processors. Since the FTS processor needs the position data at 10KHz, it is responsible for commanding the laser reads. After reading the laser, the FTS processor initiates transmission of the position data to the axis control processors.

3.7 Task Allocation

Each computational processor (i.e., C30) executes two tasks. A timer interrupt driven feedback task performs the primary closed-loop control update function allocated to a given processor. The other task executing on each C30 is an asynchronous communications task. Control of the FTS, X
axis, and Z axis is separately allocated to individual computational processors. These periodic tasks execute at 10KHz, 2KHz and 2KHz respectively. The system control processor feedback task is allocated to a fourth computational processor and updates machine state information at a much slower 10Hz rate.

The system control processor communications task accepts commands from the host, processes them, and sends the appropriate messages to the control processors. The communications task on the control processors (FTS and axes) handles the receipt of incoming messages and modifies the feedback task state accordingly. Since the feedback and communications tasks share critical data a mutual exclusion mechanism is used to prevent data corruption.

3.8 Real-Time Data Communications

A key design consideration in the implementation of this system is the means of real-time interprocessor data communications [1]. For example, as noted above, the laser position data must be transferred from the FTS controller to the axis controllers at a 2KHz rate. Based on an evaluation of the interprocessor communications performance of a generalized message passing service in the H²-ART architecture, an application specific interprocessor communication service is required.

In the H²-ART architecture concept, message passing is the responsibility of the node controller. H²-ART operating system software includes a generalized interprocessor message passing facility. This facility provides for all interprocessor data flow in the DTM/FTS control system, except transfer of laser position data. Communication of laser data requires higher performance than provided by the generalized message passing facility. The generalized message passing facility transfers data between computation processors at rates of $1.0\mu s$ (intranode) and $2.8\mu s$ (internode) per 16-bit word. Message passing overheads are $276\mu s$ and $404\mu s$ respectively. Using the general communication package, the internode transfer of the 64-bit laser position data takes
415\mu s. Thus the overhead makes the latency of the generalized message system too large for timely transfer of laser position data from the FTS control processor to the X-axis and Z-axis controllers. Reducing the communications overhead reduces the latency between feedback inputs and calculated control outputs [2].

Implementation of a virtual circuit facility for frequent transfers was considered and discarded due to estimated intranode and internode overheads of 125\mu s and 250\mu s respectively. To provide the higher interprocessor communication speeds desired for the FTS control, the serial I/O ports of the C30 were used. These ports can transfer data at rates up to 520,000 16-bit words per second. The two ports on the FTS controller directly connect to the X-axis and Z-axis controllers. Since these paths are dedicated to transfer of laser position data, the overhead is very low. These direct interconnections transfer laser position data blocks at a rate of 8.0\mu s per block.

4. CONCLUSION

The scalable, open features of the Heterogeneous Hierarchical Architecture for Real-Time permit the design and implementation of advanced, high-performance control system strategies. The Diamond Turning Machine with the Fast Tool Servo enhancement is a unique system with demanding computational requirements. A prototype has been implemented that demonstrates ultraprecision capability in an important manufacturing area. Also, the stage has been set for continued improvement in manufacturing quality and precision.
REFERENCES


