PROCESS DATA ACQUISITION:
REAL TIME AND HISTORICAL INTERFACES

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Process Data Acquisition:  
Real Time And Historical Interfaces

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ABSTRACT

With the advent of touch probe technology, it was discovered that current closed architecture controllers do not provide adequate resources to support the implementation of process data acquisition on the shop floor. At AlliedSignal Federal Manufacturing & Technologies, a process data acquisition system has been developed for a flexible manufacturing system utilizing touch probes and customized software which allows fixture and cutting tool related information for an entire process to be captured and stored for off-line analysis. The implementation of this system, the difficulties and pitfalls, will be presented along with the functionality required for an open architecture controller to properly support process data acquisition.

Keywords: process data acquisition, process control, touch probes, flexible manufacturing

1. INTRODUCTION

The Federal Manufacturing & Technologies (FM&T) division of AlliedSignal Inc. manages and operates a highly diversified, world-class manufacturing and production facility for the Department of Energy (DOE). In 1991, FM&T began operating a flexible manufacturing system (FMS) which is a state-of-the-art automated production facility. The facility represents a $15 million capital investment in the DOE’s manufacturing future.

The 11,500 square foot FMS facility consists of six 4-axis horizontal spindle machining centers, two automatic guided vehicles and associated material handling systems, one automatic part wash station, a central chip and coolant recovery system, and two coordinate measuring machines (CMMs). The system is controlled by a DEC Micro VAX-based supervisory control system. The facility is capable of machining and inspecting up to 32 different part operations simultaneously from a job mix of several

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hundred part configurations. Extensive use of machining center probes and custom probe software, developed by FM&T, provides a unique capability for real-time verification and control of the manufacturing process. The fully integrated CMM capabilities provide immediate feedback on process stability and the acceptability of the products being manufactured.

1.1 What process data and real time means to FM&T.

The process data collected in the FMS relates to the individual part operations at the machining centers. These data include the part number, serial number, the machine processing the part, time and date stamps, the fixture offsets for the process, what cutting tools were used, length and diameter compensations, and other process related measurements required for the process. “Real time” for this particular application could also be called “process-intermittent” since all of the parametric data is collected either while the probe is in the spindle or during a tool change. The data taken from the process is uploaded at the end of the manufacturing cycle and stored on-line for analysis and troubleshooting.

1.2 Why current controllers do not support data acquisition.

There are three key issues why the current and past generations of machine tool controllers do not support process data acquisition. First, most controllers were designed and optimized specifically for motion control and execution of numerical control programs. Second, in many cases the entire control unit is packaged into a black box, totally inaccessible by the end user (i.e., closed/proprietary architecture). Last, and perhaps most important, most controllers use some form of executive software which looks like ladder logic as opposed to an operating system found on modern PCs. These factors limit the development of end user software and the use of off-the-shelf hardware/software components to facilitate data acquisition.

2. PROCESS DATA ACQUISITION SYSTEM (PDAS)

The Process Data Acquisition System (PDAS) is a collection of different systems that collect, move, store, and analyze process information from the FMS. The system is comprised of four major systems and two supporting systems. The four major pieces are the software and hardware at the machine (including a touch probe) collecting and generating raw data files, software to analyze the raw data files and place them into the data base (parser), the data base that maintains the data, and the interface tools used to view the data. The supporting systems are the network that ties all these devices together and a process on the FMS supervisory computer that adds part number, part serial number, and time stamp information to the raw data file.

Data is collected and moved to the PDAS data base through a series of independent systems. Points are collected off the part at the machine tool utilizing the touch probe to make the physical touches and the original equipment manufacturer’s touch probe software. Specialty software in the machine control (written by FM&T) capture these points and apply process controls based on this data. At the completion of the part process, this specialty software bundles selected part data points along with information about the process and the process controls used on this part and sends this data to the FMS.
supervisory computer. The data file waits here for about one to three minutes until a program on the supervisory computer adds a header record to the file containing information not available at the machine control. The part data points in the file and header record information are inserted into the Quality Information System (QIS, an OEM part of the FMS) for later retrieval. The data file is then moved to another directory to await further processing. A process on the UNIX machine (home to the PDAS data base) pulses this directory every five minutes and pulls across awaiting data files. This process (parser) assigns a unique ID number to the data set and inserts the data into the PDAS data base after verifying the data file is not already in the data base and validating the files contents. The data is then available for analysis or review by the FMS staff. Total elapsed time from part process completion to availability in the data base is approximately ten minutes.

2.1 Touch probes - The key to physical data collection.

The FMS was designed to be operated unattended for the machining operations. This method of operation requires tighter process controls to be in place than for a standalone machine with an operator present. Without an operator, the process must be able to make adjustments "on-the-fly" to itself to compensate for differences in the machining centers and part and cutting tool variability. The touch probes and their associated software perform many of the same functions an operator performs to set up and run a job on a standalone machine. The touch probes, however, are substantially more consistent and repeatable for calculating fixture and cutting tool offsets when compared to human process intervention. In addition, data can be collected at the same time the calculations occur, providing a historical record of the process.

The machine tools in the FMS are configured with two Renishaw touch probes per machine. Each touch probe is a sensitive multi-directional electro-mechanical switch that may be placed in the spindle of the machine tool. The first probe assembly is a Renishaw MP3 probe head holding a six inch long ceramic stylus with a four millimeter diameter ruby ball on the end. The second is a Renishaw LP9 probe head holding a six inch long ceramic stylus with a one millimeter diameter carbide ball on the end. These two ball diameters and the long stylus lengths permit touching a wide range of manufactured features typical of the parts produced in the FMS.

Operation of the probe (supplied by the OEM) is relatively straightforward. The probe communicates with the machine via magnetic coils on the probe and in the face of the spindle. The signals sent from the probe to the machine are a carrier wave and open/closed probe contacts. The probe contacts are normally closed and then open when the probe tip is deflected by contact with a surface. The machine watches for the status change from closed to open. On the change in status, the machine control captures the current axis positions for software analysis. The machine handles all axis motion prior to and following the touch as well as interpreting the direction of the touch independent from the probe.

Calibration of the probe styli is accomplished using a 0.625 inch diameter bushing with a known actual diameter. The bushing is located inside the machine enclosure. The location minimizes exposure to chips and machine coolants yet is accessible to the probe while in the machine spindle. The process of calibration consists of a series of six touches placing the center of the spindle coaxial to the center of the bushing, followed by a series of four touches (+ X-axis, - X-axis, + Y-axis & - Y-axis) to establish the probe tip offsets. Plus and minus motion offsets are stored for both the X and Y machine axes. These
offsets are calculated by comparing the reported bushing size with the known size. Each offset is adjusted so that future touches of the bore would report the actual size of the bushing.

2.2 Philosophy of process control with touch probes

FM&T recognized early on that process control in the FMS would be different than traditional process control. Most of the drivers for this were related to the absence of the machinist. Many alternatives were considered but using touch probes for a data source combined with limit-based process control software offered the best starting point for process control.

The immediate problems were the generation of fixture offsets and adjusting cutting tool compensations. FM&T’s 14 years of experience applying touch probes in a traditional shop floor environment supported that the probe could do these tasks. However, all the experience was based on human supervision of the probe and process. The human element would clearly not be present in the FMS, and the probe was known to be sensitive to burrs and foreign material. Who or what would detect these conditions and control or monitor the probe?

The solution to these problems was the creation of process control software at the machine tool. Complete control of the process was given to this new software so it would be self monitoring whenever possible. For areas where a software solution was not adequate, the process would need to be robust enough to prevent problems.

Controls built into each process became the location of the fixture locating hole(s) and burr management. Fixture locating holes must be positioned in areas that either prevent contamination or are easily cleaned by coolant and air at the machine. Once the probe touch locations are identified, the cutting process must be designed to prevent or remove burrs in those areas. This is accomplished (1) by using a chamfer cutting tool to machine a 0.010 inch break on the edge of the part, (2) by controlling the direction of cut to not generate burrs, and (3) by making an additional pass with the tool generating the surface to cut off the burrs.

Probe Calibration: Data collected from the touch probe is integral to all of the process control steps incorporated in the FMS. Maintaining accuracy of the probe system is paramount to controlling the process. The probe is calibrated using the OEM calibration software, with the following process control features added: (1) Each time the probe is brought into the spindle, the current time is compared with the last calibration time. Currently, a recalibration is done if the elapsed time exceeds eight hours. (2) The new and old calibration values are compared. Differences of more than 0.0002 inches cause a stop in the process, requiring human intervention.

Data Captured: Each touch probe calibration results in either a successful or unsuccessful calibration attempt. Either way, the touch probe identity number, calibration time, and offset values are recorded to the machine control data file.

Data Use: Calibration values that do not repeat can indicate one of several conditions: (1) The calibration bushing is dirty or damaged. (2) The spindle housing is dirty. (3) The touch probe stylus
is damaged. (4) The touch probe is damaged. (5) The machine coordinate system has changed
(could be thermally caused).

Part and Fixture Setup: In a traditional manned machining environment, the part fixture is placed on the
machine and adjusted to match the machine coordinate system each time the operation is prepared to
run. These adjustments include the X-axis center, Y-axis center, Z-axis center, and aligning to the
machines’ X-Y, X-Z, and Y-Z planes. Machining parts in an unmanned environment required the same
type of part and fixture adjustment. This may be accomplished with one of several approaches.

First: The pallet and fixture can be moved to a machine and adjusted like in a traditional manned
environment. This approach requires taking a machine off-line for the 15 to 30 minutes required for
the machinist to complete the activity.

Second: The fixtures and pallets can be produced to tolerances that, when mated together, properly
position the part in the machine coordinate system. This approach is very expensive when applied to
a system like the one in FM&T. Sixty fixtures and 50 pallets all must be produced such that any
combination would properly position the part in the machine coordinate system.

Third: Create a station in the FMS or cell where fixtures and pallets can be mated together and
adjusted to match the machine coordinate system. This station would be expensive to manufacture
because it would have to simulate the machine coordinate system to very close tolerances.

Approaches 1 through 3 do not overcome one other fundamental problem. The orientation between
the pallet locators and the machine coordinate system are different for each machine. None of these
approaches compensate for this variation.

Fourth: Align the fixture to the machine with the touch probe. Utilize the rotary axis of the machine
to align the fixture with the machine X-Y plane. This is done with two touches in the X-Z plane and
adjusting the rotary axis. Then make a single touch off the face of the fixture to align the fixture to
the machine Z-axis home. Finally, find the center of fixture indicating hole to align the machine X
and Y homes to the fixture home. This approach still requires the fixtures and pallets to be
manufactured such that they take care of orientating the part in the machine’s X-Z and Y-Z planes.
However, these two axes are the easiest to control in this manner. This is the approach chosen for the
FMS.

Data Captured: The fixture offsets are generated for the process following approach four. These
offsets are stored in a fixture offset parameter table on the machine control. The parameter table is
capable of storing up to 32 separate sets of X, Y, Z, and rotary axis offsets. The contents of this table
are passed to the PDAS system.

Data Use: The entire part process is impacted by the fixture offsets in place during the operation.
Once a fixture and pallet are mated together, the fixture offsets will vary by only a small amount for a
specific machine; however, there is normally a large difference from one machine to another.
Variation in these values would generally mean: (1) The fixture has been moved on the pallet or
relocated to another pallet. (2) The touch probe is improperly calibrated or broken. (3) The pallet is
not properly locating on the machine. (4) The machine coordinate system has changed or is out of alignment. (5) The pallet clamping mechanism is not properly clamping the pallet to the machine.

**Part Load Process Verification:** The touch probe can verify proper part orientation on the fixture prior to machining. Drilled holes can be checked at the first and last hole machined. If any discrepancies are found, the program is halted and alarms stop the process for human intervention. These controls are used only on parts where there is a possibility of incorrect loading or where a tool failure would significantly effect the remainder of the process.

**Data Captured:** Data for incorrectly loaded parts is not captured. These processes typically terminate (due to detection) before any machining occurs. The method of termination at the machine typically prevents a successful upload of the machine data file from the machine.

**Cutting Tool Compensation Management:** Cutter compensation adjustments are accomplished by measuring part surfaces with the touch probe. The resulting measurement is compared with the expected value for the surface. The deviation value is fed to a compensation routine. Pre-set limits control minimum change, maximum change, and total change from the original compensation values for a cutting tool. These limits may be overridden by any part program, allowing complete control of each tool. Compensation values smaller than 0.0003 inches are not applied. This is to prevent the process from oscillating the process centerline with compensation values that are near the accuracy of the probe feedback system.

**Data Captured:** Each cutter compensation attempt sends (to the machine data file) the identity of the cutting tool, time of occurrence in the process, the previous compensation value, the new compensation value, and whether the compensation is on diameter or length. Data for both accepted and rejected compensations are saved.

**Data Use:** Rejected and small compensation values are a normal process sign as tool wear is recorded in these values. Larger values would be expected for part materials that are more difficult to cut; however, large compensation values can also be a sign of a problem in the process: (1) the tool may be improperly applied, (2) the tool may have been used past the end of its useful life or (3) the tool may be damaged. Another condition to look for is large oscillations in the cutter compensation value. This is generally a sign of improper cutting conditions on one of the operations using the tool.

**Cutting Tool Use:** Each process in the FMS uses between one and 35 cutting tools. In a traditional manned machining environment, the machinist monitors tool usage and tool life. In the event of any type of problem or failure, the machinist can immediately associate the problem with the offending tool. In an automated system, a tool may be used again or even removed from the system before any part problems are detected. Without data like the machinist provides in the traditional environment, corrective action for problems can be guesswork at best.

**Data Captured:** For every tool that is used in the process, the cutting tool identity number, time loaded in the spindle, time removed from the spindle, and the current length and diameter compensations are saved to the machine data file.
Data Use: When a tool fails prematurely or if a part is detected with an out of tolerance feature, the cutting tool usage information is useful in detecting cutting tool related problems. Typical problems that can be detected are: (1) tool was used too long, (2) tool was improperly used during this or a previous operation, (3) interaction between the way two operations use the tool.

2.3 Normal process flow

The following is an overview of a normal FMS process at the machine tool. Each process step lists the process controls in place for that step as described in the previous section.

<table>
<thead>
<tr>
<th>Step</th>
<th>Process Description</th>
<th>Related Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load probe into spindle and verify calibration.</td>
<td>“probe calibration” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>2</td>
<td>Calibrate if required.</td>
<td>“probe calibration”</td>
</tr>
<tr>
<td>3</td>
<td>Establish fixture offsets.</td>
<td>“part and fixture setup”</td>
</tr>
<tr>
<td>4</td>
<td>Verify part load or location.</td>
<td>“part load/process verification”</td>
</tr>
<tr>
<td>5</td>
<td>Begin machining part.</td>
<td>“cutting tool use”</td>
</tr>
<tr>
<td>6</td>
<td>Make trial cut for critical finish tools.</td>
<td>“burr management” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>7</td>
<td>Clean part and fixture with coolant and air to remove foreign material.</td>
<td>“burr management” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>8</td>
<td>Load probe into spindle and verify calibration.</td>
<td>“probe calibration” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>9</td>
<td>Calibrate if required.</td>
<td>“probe calibration”</td>
</tr>
<tr>
<td>10</td>
<td>Check part features and adjust tool compensations.</td>
<td>“cutting tool compensation management”</td>
</tr>
<tr>
<td>11</td>
<td>Make finish cuts on part.</td>
<td>“burr management” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>12</td>
<td>Clean part and fixture with coolant and air to remove foreign material.</td>
<td>“burr management” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>13</td>
<td>Load probe into spindle and verify calibration.</td>
<td>“probe calibration” &amp; “cutting tool use”</td>
</tr>
<tr>
<td>14</td>
<td>Calibrate if required.</td>
<td>“probe calibration”</td>
</tr>
<tr>
<td>15</td>
<td>Make any final tool compensations.</td>
<td>“cutting tool compensation management”</td>
</tr>
<tr>
<td>16</td>
<td>Process is complete.</td>
<td></td>
</tr>
</tbody>
</table>

Data about the process is collected and written to the machine data file during each of the software controls listed above. Some machine tool overhead is incurred collecting process data at the machine tool. For simple operations, such as roughing or facing, the probe portion of the machine cycle may be as much as 50 percent of the overall cycle time, with other software controls adding an additional 2-3%. Of this additional time, 50% is spent waiting on the controller to process the data collected. On complex operations (a large number of finished dimensions being produced), the percent of the machine cycle time consumed for process control is very small; however, the total time of non-cutting work does increase. The benefits of using this approach for unattended process control far outweigh the additional cycle time incurred.
2.4 Storage of Process Data

The Oracle Relational Data Base product was chosen as the tool to store the process data. The data base must be on line 24 hours a day to support three shift operations in the FMS. Data must be accepted in near real time while permitting technical and manufacturing staff access on demand. The data base must support a C programming interface for development of data input and analysis routines. Oracle met these requirements as well as being one of the tools that the FMS technical staff was already using. The data base and supporting UNIX computer were already in place.

3. IMPLEMENTING PDAS SOFTWARE

Implementation of the PDAS software required development activities on several different systems. First, process control and data manipulation routines were needed at the machine tool to work with the probe data. Next, modifications to the supervisory control software were made to allow the machine data file to be uploaded and processed. Finally, software and services were built to pull the raw data from the supervisory control system and populate the Oracle data base.

3.1 Process Control Software at the Machine Control

Subroutines were developed by FM&T to automate machine tool process controls in the FMS. In general, the subroutines provide an action (i.e., tool diameter compensation) and then record the action and data for PDAS, QIS, and/or the LOCAL file. Data used to support these process control actions is collected with software supplied with the machine. The major subroutines which make data acquisition possible on the machine tools are listed below.

STARTUP: A call to the STARTUP subroutine is made at the beginning of every part program. This program initializes any variables or program names required to support follow-on subroutines. This includes:

1. Create CLEANUP file -- used to delete temporary files at the completion of the program.
2. Create PDAS file and record starting spindle temperature.
3. Create QIS file.
4. Create and open LOCAL file -- process summary available at the machine during the process.

CLOSEOUT: The CLOSEOUT subroutine is responsible for clearing the variables and files generated during part program execution. It leaves the machine ready for the STARTUP call for the next part. The program will also push the QIS and/or PDAS file(s) to the FMS supervisory control and print the LOCAL file if they have been specified.

LOAD.PROBE: The LOAD.PROBE subroutine performs the following functions:

1. Execute the wash cycle if the part has coolant on it.
2. Load the probe into the spindle.
3. Record current values for the probe stylus offsets and time stamp for PDAS.
4. Calibrate the probe if current time and last time calibrated exceeds system limit (if more than 8.0 hours, execute DATUM.PROBE subroutine).

**DATUM.PROBE:** The DATUM.PROBE subroutine executes the following:

1. Read in current X, Y, Z tool post positions and radius of calibration bushing if not defined.
2. Execute a G25 cycle (calibration cycle).
3. Compare old and new probe stylus offsets for repeatability (re-calibrate if necessary).
4. Write new values for time stamp and probe stylus offsets to the PROBE file.
5. Write values for time stamp and probe stylus offsets to the PDAS file.
6. Write values for time stamp and probe stylus offsets to the LOCAL file.

**TLCHNG:** The machining centers utilize serialized tooling. This means that a machine may have more than one copy of a tool assembly. The tool copies are uniquely identified by serial numbers assigned by the Tool Manager software in the FMS. For example:

Tool assembly number 2000001 would be a tool programmed as T20000 with a serial number 01 assigned to it.

Serial numbers may range from 00 to 99 in the FMS. Therefore, it is possible to have 100 copies of a given tool assembly. Since the part program only knows the base tool number (Txxxxx), it is necessary to capture the serial number of each tool at tool change. The subroutine TLCHNG was created for this purpose.

TLCHNG creates two temporary files to store tool information. The first one, a file called “**TOOL xxxxxzz.1 ORIGINAL,**” is created and stores the tool number, serial number, length, and diameter compensation values set by the tool setter for the tool when it was new. These values can be used later by the LENCOMP and DIACOMP subroutines to determine total compensation applied to a tool. The second file is called “**TOOL xxxxx.0 CURRENT**” and is used to store the current serial number and the compensation values of the tool being used. This file is also used by the tool compensation routines.

TLCHNG also creates DLF statements that will delete the temporary files created. Information may also be passed to PDAS and the LOCAL files if requested.

**DIACOMP:** The subroutine DIACOMP is used to change diameter compensation. It will update the tool offset table, format PDAS information, and write to the LOCAL file. It has default values but also allows the programmer to set incremental limits of diameter compensation (both minimum and maximum) as well as a total compensation amount. Plus compensation leaves plus material on the machine tools. For example, on an external width cut (i.e., a boss), plus diameter compensation will cut a larger external feature. Conversely, on an internal feature (i.e., a slot) plus diameter
compensation will cut a smaller internal feature. Therefore DIACOMP must know the type of compensation being done. The default is external compensation.

Generally, most diameter compensation is based on two touches by the probe that establishes an actual distance that can be compared to an expected dimension. Sometimes it is necessary to use just one touch. When this happens, the compensation type must be declared by telling DIACOMP the probing direction.

DIACOMP reads the temporary files created by TLCHNG to obtain the offset data for the current tool as well as the original values. It also reads the file called "TOOL xxxx.zz COMP" to see if the tool has already been diameter compensated on this run. If it has, DIACOMP is exited without performing any compensation. If the tool has not been compensated, DIACOMP will calculate the diameter compensation required and check the amount against limits set by the system and/or the programmer.

DIACOMP has three optional parameters that provide a way to limit the amount of compensation. One is used to set the minimum amount of compensation allowed for one adjustment (defaults to 0.0003 in.). Another sets the maximum amount of compensation that may be applied for one adjustment (defaults to 0.004 in.). The last sets the total amount of compensation allowed for the life of the tool (defaults to 0.010 in.).

If the compensation amount falls within limits, the tool table is modified and the temporary files are updated. If the total compensation limit is exceeded, the tool status is set to warn. If the maximum one-time limit is exceeded, the program stops and an alarm sounds. The compensation amount must be verified by a machinist before resuming the program. There are two program stops in a row to ensure positive verification.

LENCOMP: The subroutine LENCOMP is used to change length compensation. Like the DIACOMP subroutine, LENCOMP will update the tool offset table, format PDAS information, and write to the LOCAL file. It has default values but also allows the programmer to set incremental limits of length compensation (both minimum and maximum) as well as a total compensation amount.

Plus length compensation will move the tool away from the work piece (Z+ direction). Height compensation compares an actual Z coordinate with an expected Z coordinate. Depth compensation compares an actual depth measurement (done with two touches, top first, then bottom) to an expected depth. Therefore, LENCOMP must know the type of compensation being done. The default is height compensation.

Generally, length compensation is based on one touch by the probe in the Z- direction that establishes an actual height from the Z reference surface (from the fixture offsets) that can be compared to an expected dimension. If a tool generates two external parallel surfaces by end cutting both with a 180 degree rotary axis move between, it is necessary to measure the parallel surfaces to find the actual dimension (measured perpendicular to the cut surface). When this happens, the calculated compensation must be divided by 2.
3.2 Modifications to the FMS supervisory control software

The Operations module of the FMS supervisory control software was modified by the OEM to accommodate the collection of probe data. The Operations module is responsible for downloading numerical control (NC) programs to the machine tools, cycle starting the machines, uploading tool table and tool event information, and uploading the machine data file from the machine tool controller. Operations is the module that builds the header record for the PDAS file and sends a message to the QIS computer that an inspection file is ready to be processed.

If the uploaded file is successfully processed, it gets renamed from `<NC_program_number>.PROBE` to `CNCINSPECTIONLOG.PROCESSED`. A batch process on the QIS computer pulls the inspection file across the network and loads it into the QIS data base. A copy of the inspection file, `<NC_program_number>.CMMPROCESSED`, is placed in a special directory where a batch process on the UNIX computer (where PDAS resides) looks periodically for inspection files to process. If the machine data file is corrupted in any way, the original file is left alone and another file called `<NC_program_number>.ERROR` is created. The .ERROR file contains diagnostic information about why the file did not properly process.

3.3 Data base design

The data base table structure is a fully normalized structure. Original plans called for tuning the data base by adding indexes and then de-normalizing the tables based on real response time. Experience so far shows that indexing has provided more than adequate response times. The table structure is shown graphically in Figure 1.

The data base is made up of 21 separate tables. The main table is titled “specific_fms_pass”. This table contains unique single occurrence information about each time a process runs in the FMS. A unique ID number is added to each process record called “fms_pass_id” as it is entered into the data base. This number is also entered into many other tables to maintain a link back to the “specific_fms_pass”. This table contains actual date, time, machine number, and other specific part and machine related information. With 13,531 records, “specific_fms_pass” contains only 2.7% of the total records in the data base.

The “specific_fms_pass” table provides links to the “prog_hcode_history”, “processed_part”, “tool_event”, and “tool_use_event” tables through the common field “fms_pass_id”. The “prog_hcode_history” table makes up 8.2% of the data base and contains all the fixture offsets generated for the processes. Links are provided to the “prgm_hcode_defn” table. This table is manually entered and contains descriptions of what that offset is used for at the machine. The “processed_part” table is 3.7% of the data base and contains the part serial numbers and location on the fixture for each part. Many of the processes in the FMS machine more than one part at a time on multi-station fixtures. The “tool_event” table is 9.2% of the data base and gets an entry each time the compensation on a tool is changed or considered for change. This table then has links to the sub-tables that contain the specific information about compensation type and amount. The “tool_use_event” table, the largest at 29.3% of the data base, receives data for each time a tool is loaded into the spindle. Links are provided to the table containing information about the type of tool event that occurred.
The “tool_use_event” has links to the “cutter_use_event”, “failed_datum_event”, and “probe_datum_event” tables. The largest with 23.1% of the data base records is “cutter_use_event”. This table contains the record of each time a specific cutting tool is placed into the spindle. Touch probe uses are not entered here and reside only in the “tool_use_event” table. The “failed_datum_event” and “probe_datum_event” tables retain information about each time the touch probes are datumed or calibrated. These tables are small, with 0.3% and 1.1% of the data base records, respectively. The “probe_datum_event” table retains the actual probe tip offset values in both English and metric units.

The largest sub-table structure in the data base is the “tool_event” group. This group is made up of eight separate tables that describe compensation events to specific tools. These tables make up 31.8% of the data base. The “diameter_comp”, “length_comp”, and “mod” tables contain the records of the compensations actually applied to cutting tools. While the diameter and length are affiliated with the diameter and length compensation on the tool, mod contains information about both. The “mod” table holds the amount the compensation on the tool changed. The “tool_comp” table goes with these three tables to show the source of the compensation. Today, only the touch probe is used to generate cutter compensations, but in the future other sensors are expected to be available. This table allows the source of the compensation to be recorded. The “validation” and “flagged_tools” tables are not currently used. The “validation” table would contain records of when two sensors were used to determine the compensation change of a tool. The “flagged_tools” table would contain information about tools flagged as bad because the two sensors could not agree on the compensation value. Only one sensor is available today. The “new_tool” table receives information about a tool the first time it is loaded into the spindle. Finally, the “passed_comp” table records the modification value for cutter compensation when the value was small enough that the software chose not to adjust the tool.

A number of other tables are listed in Figure 1 that are manually entered. These are not currently used. Original expectations were that the number of technical staff in the FMS would be large enough that the users would need tables to help convert part numbers, program numbers, and fixture offsets into people and descriptions. At this point, that has not been necessary, and the users have responded by not populating those tables.

### 3.4 Software to populate the data base

Three pieces of special software support the PDAS system on a UNIX machine where the Oracle data base resides. The first is PULLER, the second is STARTER, and the third is PARSER. PULLER has the responsibility of checking with the FMS supervisory computer for data files ready to be placed into the data base and then of pulling them across the network. STARTER receives the signal from PULLER that files are ready to process. STARTER then launches a PARSER against those files, allowing up to six PARSERS to be running at any one time. PARSER analyzes the data file and confirms the file is valid, then puts the file into the PDAS data base.

PARSER has a number of different types of errors that it detects prior to inserting data into the data base: (1) Verify each field in the Header record contains a value in the proper format. (2) Verify the file contains a “STP” and “ETS” line. (3) “ETS” is the last line in the file. (4) Each individual reporting record is complete. (5) A probe usage report line must immediately follow the “STP” line.
(6) A fixture offset must occur prior to any tool usage lines. (7) The part number, part serial number, and FMS supervisory computer time stamp from the Header record cannot already exist in the data base.

3.5 User interface

The user interface utilizes a structured query language (SQL) tool for output. SQL command scripts have evolved since the creation of the system along with the needs of the users. These views of the data have stabilized over the last year. Current plans call for converting these views into some type of WEB browsing tool that is directly connected to the Oracle data base.

Primary views of the data:

Fixture compensation report. This report collects the fixture offsets for a specific part operation. The data is grouped by the pallet number carrying the part and then by the machine that manufactured the part.

Cutting tool usage report. This report gathers all data for a specific copy of a cutting tool. The data is chronologically organized from the first occurrence of the tool to the last. The data included are every part operation using the tool, the length of time the tool was used, and every compensation attempt either successful or unsuccessful.

Specific part report. This gives a chronological list of all probe uses and tool usages. Included with each line are the current cutter compensation values for each tool and the elapsed time in the spindle.

4. CONCLUSION AND RECOMMENDATIONS

The work presented in this paper has detailed what was required to development and implement a successful process control and data acquisition system in an unattended environment using touch probes. The majority of the machine tool based process control and data acquisition software was written to "work around" missing functionality at the machine controller. Several dissimilar computer systems, networked together, were necessary to collect, process, and store the data.

The functional requirements for an open architecture (OA) controller to support data acquisition and process control can be broken down into four components. These components are:

PC-based controller: For a variety of reasons, it seems to make sense to not use home grown hardware anymore. This approach allows for the following functionality to be included with a controller.

1. Industry standard data bus (ISA, EISA, PCI).
2. Off the shelf peripherals (hard drives, CD-ROM, monitors, keyboards, RAM memory).
4. Industry recognized 32-bit, multi-tasking operating system (UNIX, NT).
Application Program Interface (API): This would allow the end user to customize the machine controller to suit their business and technical requirements.

1. ANSI C language based
2. Provides access to:
   - parameter tables
   - tool information tables
   - machine status
   - motion control
3. Provides functions for:
   - sensor data collection (touch probes, temperature, vibration, and emerging technologies)
   - real time error correction
   - closed loop process variables feedback
   - error handling and recovery
4. Real time event logging that cannot be bypassed.

Sensor Interface: The interface must be flexible and adaptable enough to allow fast introduction of new sensors into the machining process. It must provide (1) the ability to manage multi-sensor inputs; (2) the capability of taking action upon the data, and (3) the mechanisms to manipulate and store the sensor data. Sensors might be new, faster, and more accurate probes; vision-based tool condition monitoring; temperature, force and/or vibration measurements to support real time error correction.

Information Utilities: This component of the OA architecture is perhaps the most important. As the work presented here has shown, it is possible to have a tremendous amount of data and information available to troubleshoot and correct problems on the shop floor. The problem is, the knowledge to interpret the data and information are rarely (if ever) available on the shop floor where the need exists. The following capabilities would be a good first step toward providing adequate resources to the shop floor.

1. On-line, video based help.
2. On-line, video based training and maintenance manuals.
3. Hyper-text linkable to related process information (i.e., tooling data bases, CAD models)
4. Programmable so process aids may be incorporated on the shop floor.

Process control is the key to producing product to specification at the minimum cost. Past experience has shown FM&T that process control can be started with a relatively small amount of data combined with the proper evaluation and storage of that data. The next generation of machining process control software will require that more information be collected about the part, tools, machine, and even the environment that the work is being done in. Collection and management of this data inside the machine control system will be a major hurdle in developing these tools. Properly configured open architecture controllers can make this part of the task significantly easier.