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IMPROVING CNC MACHINING ACCURACY THROUGH THERMAL MODEL BASED CONTROL

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ABSTRACT

The United States Army has a requirement to machine munitions to strict tolerances so that the munitions will launch properly and the explosives will detonate correctly. High precision parts require machine tools to operate with a high degree of accuracy in order to produce parts within tolerance. Unfortunately, thermal expansion, tool wear and other impediments make high accuracy machining, especially over the long term, a difficult proposition. The idea of "smart machine tools" that incorporate model based control to compensate for errors during the lifetime of machine operation is an emerging trend. Model based control as applied to machine tools describes a computerized control scheme in which the mathematical model of the process is used to compensate for the inaccuracies that exist in the real world, at any given time. With the advent of commercial open architecture controllers, it is now easier to adapt model–based control into machine controllers to minimize process variability in order to more accurately machine parts on a daily basis. This paper looks at the incorporation of Nominal Differential Expansion as a model based control strategy to improve the accuracy of a turning machine and part tolerance. Nominal Differential Expansion (NDE) is the difference between the predicted thermal expansion of the workpiece and that of the master or scale. The theory of NDE will be discussed as well as how it was incorporated into a commercial, open architecture, CNC turning machine. The potential applications of model based control to other areas of distributed manufacturing will be considered.

INTRODUCTION

The United States Army Picatinny Arsenal is the primary site for development and engineering of Army weapons systems. Picatinny's Armament Research, Development and Engineering Center (ARDEC) conducts research, development and pilot–plant production of explosive and propellants and seeks to improved production quality and reduce the cost of munitions fabricated by its suppliers. Targets include machining of armament casings to strict tolerances, typically below 0.001 inches (20 microns). This is difficult as the Army has a multitude of suppliers who machine these munitions under a variety of plant conditions. As these munitions become more and more complicated, the onus to impart "best manufacturing practices" on the suppliers is necessary in order to capture process knowledge and distribute this knowledge along with the part geometry and tolerance information.

As part of ARDEC's research, the use of smart machine tool technology is being considered as a means to transfer process knowledge to the munitions suppliers. Smart machine tools incorporate process sensors and employ model based control to compensate for errors to improve munition fabrication. Model based control describes a computerized control scheme in which the mathematical model of the process is used to compensate for the inaccuracies that exist in the real world, at any given time. In the case of munition casing production, a variety of process and geometric errors contribute to machine inaccuracies, including machine straightness and squareness as well as tooling, fixturing, geometric and thermal errors.

Part of the smart machine tools doctrine is the notion of re-

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ducing geometric and process errors to achieve high accuracy of a machining center at all times under varying conditions thus yielding highly accurate parts. High accuracy machining has remained an unfulfilled dream, mainly due to the cost and difficulty in characterizing machine behavior for a process at any given time under differing operation. With the advent of commercial open architecture controllers, it is now possible to adapt model based control into machine controllers to minimize errors in order to more accurately machine parts on a daily basis.

One of ARDEC's test pilots was to implement model based control for munition machining in order to compensate for thermal inaccuracies in a turning center. A survey of industry finds the application of thermal compensation is predominantly used within the aerospace industry, where the parts are large and non–symmetric, and subject to large thermal discrepancy from one end of the workpiece to the other. In the case of most other machining applications, the use of thermal compensation in a proprietary machine controller is either too expensive or difficult to realize. The access provided by open architecture controllers can be integrated with thermal sensing to makes it possible to come up with cost–effective thermal compensation.

The remainder of this paper discusses the integration of Nominal Differential Expansion into an open–architecture CNC controller as a cost–effective solution to decrease thermal errors. The paper briefly reviews the issues related to thermal compensation and the rationale for using Nominal Differential Expansion. We look at the importance of open architecture technology in implementing thermal compensation in a cost–effective manner. Then we look at the use of the Model Based Control (MBC) software suite to capture the process knowledge contained in the thermal compensation as a means to distribute the knowledge to suppliers.

THERMAL COMPENSATION

Thermal errors are often the most significant class of errors affecting the accuracy of machined parts. They are also very difficult to model, predict, and reduce. Thermal errors are caused by thermal expansion of the workpiece, master, and machine structure. Contributors to thermal errors include various heat sources, internal and external to the machine.

Plant conditions can greatly affect workpiece size. In aerospace applications, aluminum workpieces can change length by 0.1 inch or more in a few hours, responding to changes in plant environment [1]. Ideally, standard operating conditions could minimize some thermal errors through the use of air conditioning to reduce thermal errors in an attempt to control the operating temperature to the ISO reference standard of 20°C / 68°F. This can be an unrealistic cost to burden low volume machine shops.

Internally, the machine tool undergoes thermal fluctuations as part of the machining process. The faster and harder the machine and spindle operate, the hotter the axes, spindle and tool get, with heat sources including the bearings, belt and/or gear drive system, and the motor itself. Machine thermal errors are primarily due to expansion and contraction of the part, tool, spindle, and machine slides. Temperature changes that cause the leadscrew to expand or contract affect machine geometry and cause positioning errors.

To improve machining accuracy, one must compensate for the temperature changes. Our goal was to come up with an easy, cost–effective, and repeatable way in which to handle the errors. There a number of potential solutions for thermal compensation [2]. Thermal compensation can be based on a coefficient of expansion for the workpiece and adjust all axes with the same factor, depending on the sensitivity of the stock material. Complex thermal compensation may be required for thermally sensitive, asymmetrical parts where expansion and contraction rates can vary dramatically from one area of a part to another. More complex schemes involve volumetric calibration and compensation of machine tools to improve machining accuracy, but these techniques are costly as well as complicated. Once again, cost is major consideration in realizing smart machine tool technology in a machine shop.

In order to accommodate the widest audience of munition suppliers, we determined that model based control using Nominal Differential Expansion (NDE) would be the most effective way to incorporate thermal compensation across the range of potential suppliers. NDE uses the difference between the predicted thermal expansion of the workpiece and that of the master or scale to compute compensation values. Since thermal values change slowly, the magnitude of changes in machine compensation would be on the order of seconds. Differential thermal expansion causes machining errors when 1) the workpiece and machine scale(s) have a different temperature and/or 2) the workpiece and machine scale(s) have a different coefficient of thermal expansion and are at a temperature different from the reference temperature (20° C or 68°F). NDE compensation is achieved by measuring the temperature of machine scales and workpiece, and calculating their thermal expansion. There are three limitations to the use of NDE compensation as a general solution.

First, although NDE compensation significantly reduces errors that occur when machining parts in an environment different from 20°C, it does not eliminate the need for environmental temperature control when high accuracies are required.

Second, only uniform, stress–free, thermal workpiece expansion was considered. Deviations from this assumption occur for thermally aggressive machining processes, such as dry machining at high material removal rates of workpieces with low thermal conductivity. Such processes induce large local temperature gradients in the workpiece, that change rapidly in time, and whose effects are difficult to model and predict. Another deviation occurs when the fixturing of the workpiece restricts its thermal expansion. This effect can be reduced by good operating procedures, such as re–clamping the workpiece after spraying it with coolant.

Third, although compensation for differential expansion addresses an important class of thermal errors, other major thermal errors remain. These errors are introduced by the deformation of the machine structure and guideways in response to changes in internal and external heat sources. An example is the drift introduced by the heat generated by the spindle.

Equipment needs of predictive NDE compensation includes temperature sensors to assess the temperature elevation of machine scales and workpiece. Suitable temperature sensors include: thermocouples, resistance temperature detectors, thermistors, and infrared sensing. For our initial testbed, we selected thermistors as they are now relatively inexpensive and accurate. In order for thermal compensation values to be calculated, an effective coefficient of thermal expansion for the workpiece is required [3], which we had the operator enter. Because of the difficulty in attaching a sensor to the workpiece, and the cost associated with using a infrared sensor, we used a thermal sensor in the coolant to approximate the actual temperature of the part. Using this cost–effective scheme, the NDE thermal error compensation required the following elements:

- Temperature sensors and data acquisition
- Thermal error model
- Thermal compensation algorithm
- Access to the controller leadscrew tables or other position compensation mechanism
- Workpiece coefficient of thermal expansion

OPEN ARCHITECTURE CONTROL

Traditionally thermal compensation has found limited success due to the cost and difficulty of implementing the technology in proprietary controller. Previous work at NIST [4] has demonstrated that it is possible to measure thermal errors and then circumvent a proprietary CNC by injecting the compensation signal into the servo control loop hardware in the form of an analog voltage. Clearly, this is not a trivial undertaking. Fortunately, the trend towards open architecture controllers reduces the difficulty and cost associated with integrating thermal compensation and machine control.

CNC controllers built with high–volume, commercial off–the–shelf software and hardware products are called PC–based controllers. An open–architecture controller extends this PC model by providing a well–defined, flexible, and programmable controller interface that is available to all, either as a formal or de facto standard [5]. By definition, an open–architecture provides open access to real–time data and information that can be used to integrate thermal compensation into the machining process in a cost–effective way.

Figure 1 depicts the equipment used in the thermal compensation testbed**. The turning CNC on which we performed NDE

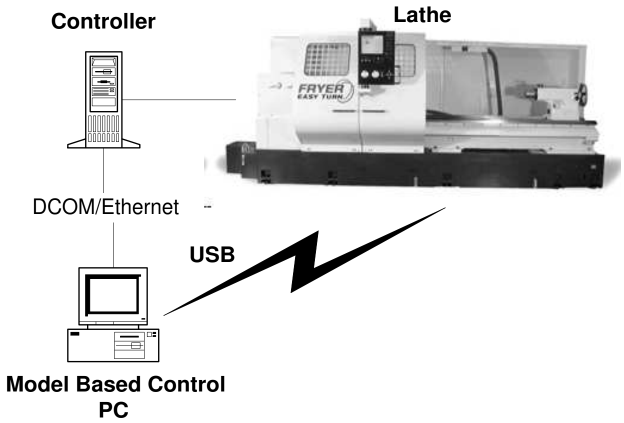

Figure 1. MBC System Hardware

thermal compensation was a Fryer Lathe, with repeatability on the order of +/-0.005mm - 0.0025mm and spindle speeds ranging from 5 - 1,500 RPM. The Fryer lathe runs a Manufacturing Data Systems, Inc, (MDSI) [6] controller. The MDSI controller uses general–purpose off–the–shelf PC hardware and software and adapted it to the more stringent needs of the factory floor. As an open architecture controller, the MDSI controller provides the OpenCNC Application Programming Interface (API) to allow manufacturing software engineers access to the internals of the controller. This access allows developers to customize their applications based on their needs.

The MDSI executes within the VenturCom RTX real–time kernel, which is a hard real–time extension for Windows that provides high–speed and deterministic real–time capabilities [7]. RTX executes as a Windows XP kernel device driver, that can preempt Windows to process real–time interrupts running inside real–time tasks and can defer Windows interrupts and faults while running real–time tasks [8]. The MDSI controller runs as a set of deterministic real–time processes and provides a real–time subsystem API through RTX and a non–real–time programming through Windows. OpenCNC allowed us to simulate the CNC thermal compensation application offline, in software, before we integrated it with the machine tool, preventing hardware mishaps and greatly reducing development time.

The thermal compensation was integrated using MDSI shared memory to access to internal controller variables. The process to perform thermal compensation was to capture the thermocouples readings using a USB Data Acquisition board, use NDE to compute updated leadscrew compensation tables to compensate for the thermal errors, and then load the new leadscrew values into the MDSI controller. We used the MDSI leadscrew tables, as this offered a simple and timely solution to correcting machine positional errors. Leadscrew compensation is represented in the MDSI controller as a two dimensional table stored in shared memory. The leadscrew compensation table is read in at startup and normally remains constant throughout the operation of the controller. We used the access to the leadscrew compensation table to compensate for any thermal expansion (or contraction) that will occur during machining.

For our initial temperature data acquisition, we used a IO plug–and–play product communicating through the PC Universal Serial Bus (USB) port. The USB provides both power and connectivity through the cable that can be hot–swapped while the PC is on without rebooting. The USB interface is external, so the PC does not need to be opened to add an IO card. The Data IO product included a C++ programmer software interface that was wrapped as a component, which will be further discussed in the next section.

MODEL BASED CONTROL SOFTWARE

ARDEC sponsors the development of a Model Based Control (MBC) software suite useful in any step of a production lifecycle where there are commercial controllers integrated into the munition production process such as batch processing of materials, machining operations, welding operation, packaging operations etc. The MBC is a software suite that runs on a standard PC and connects to controllers and other devices via Ethernet, directly or through a server, either locally or over a remote connection. The MBC communication uses Microsoft's COM standard (Component Object Model) and can interface to a broad range of off–the–shelf devices. MBC supports rapid development in a drag and drop environment using Microsoft COM components that support a type library. This tight integration of COM allows rapid control logic testing and deployment in process solutions.

The Microsoft Component Object Model (COM) is a framework for creating and using components [9]. COM is the Microsoft architecture for local interaction of components and the Distributed Common Object Model (DCOM) provides the methods for remote interaction of components. DCOM is the basis for distributed communication, and is designed for use with multiple network transports. COM provides many services to facilitate component technology including, location transparency, security, registry, naming, and type information. COM supports location transparency by allowing components to be deployed as in–process dynamic linked libraries, or as local servers, or as remote servers. The in–process COM components impose practically a zero sacrifice on performance, while local servers use Interprocess Communication (IPC) and remote servers can use multiple network transports, primarily Remote Procedure Calls (RPC).

The MBC software development environment is similar to the "drag and drop, "design and runtime, programming paradigm of Visual Basic [10], but is geared toward process and manufacturing engineers. The MBC incorporates timing and synchronization primitives necessary in control logic. In MBC design mode, programmers use the MBC to develop model based recipes by selecting from the available COM components, dragging specific functions from the COM components into a recipe step and filling out the COM function, timing and synchronization parameters. Timing and recipe step synchronization are part of the MBC software development paradigm and are critical in control programming. The user compiles the design recipe and then in run–time mode, executes the recipe. The MBC compiles the recipe into Visual Basic but also allows design–time interactive testing, so that COM components can be tested in isolation.

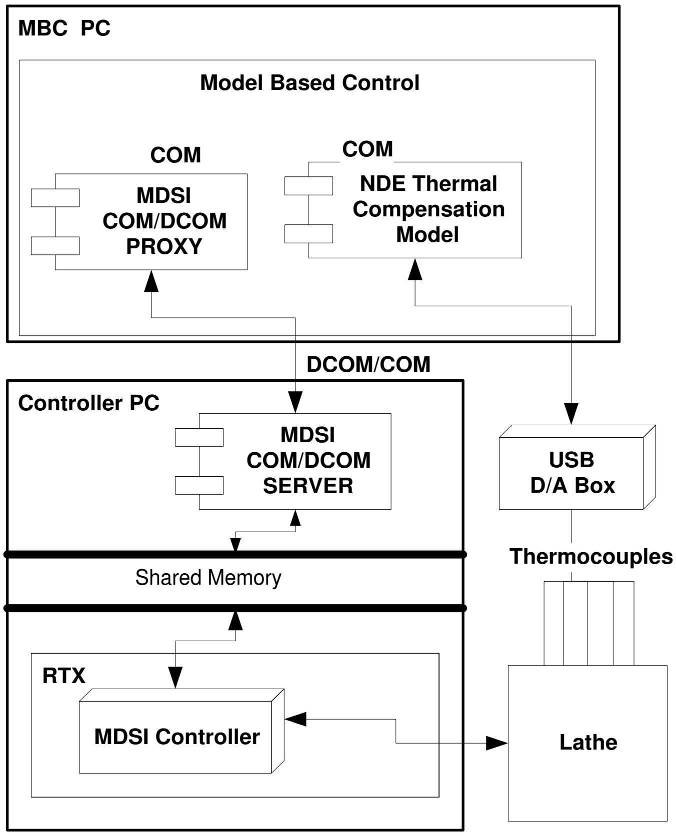

Figure 2. MBC Software Architecture

Figure 2 shows the components that were used in the MBC thermal compensation. Distributed COM (DCOM) allows the distribution and communication of component software to be relatively transparent, so that the MBC software could be tested on a single platform or across platform depending on minor configuration adjustments. Using the MDSI API, we developed a Microsoft COM server component to communicate to the MDSI controller and the Fryer lathe. Separately, a COM in–process component was developed to capture thermistors readings using the USB Data Acquisition board, and then using NDE compute updated leadscrew compensation tables. These components were then easily integrated and tested using the MBC software.

DISCUSSION

Experimental and simulation results showed that the geometric accuracy of the machine can be improved by the NDE thermal error compensation control technique, but is dependent on the range of fluctuation in the environmental and machine temperature. If the temperature fluctuation is minimal, such as in a well–controlled 20° C operating environment, then the compensation will be minimal also. However, workpiece temperature variation can effect accuracy, as the Society of Manufacturing Engineers [11] states the coefficient of expansion for plain carbon steel as 0.0000113 per degree Celsius change in temperature and Aluminum (7075) as 0.0000234 per degree Celsius change in temperature.

Significant errors can result even if the workpiece increases by only 1° C as reflected in higher coolant temperature or ambient temperature. Under such conditions, if the workpiece is machined to the correct size at an elevated temperature, the workpiece will be too small when measured at the reference temperature of 20° C. Assuming stress–free thermal expansion, the Δx_w error for the workpiece along X equals:

$$\Delta x_w = -\int_{x_r}^{x} \alpha_w (T_w - 20°C)dx \tag{1}$$

where α_w denotes the effective coefficient of thermal expansion of the workpiece causing a displacement of the tool when moving the X–slide from an arbitrary reference point x_r to point x.

Complete NDE thermal compensation used temperature readings from the coolant, which approximated the workpiece temperature, and two temperature sensors along X,Z axes. Given these readings, the leadscrew table was dynamically modified to reflect temperature changes. In a turning machine, lead screw compensation corrects for positioning inaccuracies in each axis produced by mechanical play between the ballscrew and nut. Leadscrew compensation consists of a table of error offsets at fixed intervals along the X,Z axis in a positive or negative direction of travel that correct for measured inaccuracies. We modified the leadscrew offsets based on a NDE compensation value calculated from the reference x_r at an axis minimum (or maximum) travel point to a leadscrew interval point x.

The heat generated by a machining part can have a significant impact on the part temperature. Krasovec cites tests at Caterpillar Engines that found that part temperature can increase 12°F (6°C) over the ambient temperature in unregulated plant conditions [12]. Such temperature variation can cause an engine crank bore run on nominal to be out of tolerance. To get an understanding for the magnitude of thermal error, applying equation (1) to machining a piece of aluminum stock given a reference point of $x_r = -510mm$ at the minimum of X travel and a displacement along the workpiece at point $x = 127mm$ in the leadscrew table yields,

$$\Delta x_w = -\int_{x_r}^{x} 0.0000234(26°C - 20°C)(127-(-510))mm \tag{2}$$

or a calculated error equal to

$$\Delta x_w = -0.0894348mm \tag{3}$$

compensating for thermal error in just the workpiece alone. There does exist the possibility that the thermal expansion of the X scale and the workpiece could cancel, if both the axis slide and the workpiece have the same temperature and the same coefficient of thermal expansion.

The NDE thermal compensation was implemented using MBC in a second adjoining PC, using a DCOM connection to update the leadscrew tables. The off–loading of smart functionality has the potential for many cost–savings benefits. Thermal compensation on a per machine basis is clearly more cost–effective than injecting signals into the hardware servo loop of a proprietary controller, but by itself, is not reason enough to implement thermal compensation. Another important aspect to the MBC is the leveraging of component–based technology and a PC–based open architecture controller to readily distribute this knowledge in a simple and flexible manner. The ability to substitute different COM component to communicate with different controllers, while maintaining an identical interface, modularizes any potential hardware or software changes that would be expected for porting the application source to different PC–based open architecture controllers.

More significant, research and development of process–specific knowledge need not be lost, but instead can be captured and distributed by the MBC with the part geometry and tolerance information. Deployment of any new MBC process enhancements can be packaged and shipped as a separate application that runs independently of the controller. Finally, the MBC could be used outside the realm of control for quality monitoring and historical information gathering.

CONCLUSION

This paper describes Model Based Control for NDE thermal compensation that was integrated into an open–architecture CNC turning testbed for machining Army munitions. The CNC turning testbed demonstrated the feasibility and simplicity in realizing smart machine tool technology in an open architecture controller to improve machining accuracy.

The implementation of thermal compensation MBC was the first step in quest for cost–effective machine accuracy improvement and a smarter CNC. We are looking at improving the machining accuracy by doing in–process probing to compensate for straightness and squareness errors. Ideally, the machine's volumetric errors should be compensated by MBC over the whole volume to improve overall accuracy of the machine tool, not simply its linear geometric errors.

DISLCAIMER

** Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or the Picatinny Arsenal, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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