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Machine tool performance: past and present research contributions from the Centre for Precision Technologies

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Abstract

This paper outlines the detailed investigations that have been undertaken to avoid, measure and correct for process errors that affect the volumetric accuracy of machine tools.
The areas examined include the CNC machine tool design, assembly and calibration phases of build. Complete machines and constituent elements of machines were investigated for the determination of geometric, load and thermal errors. The correction methods discussed are mainly of the pre-calibration type.

1 Introduction

The Centre of Precision Technologies (CPT) provides services and support to industry as well as an outlet for the research activities. It undertakes contract research sponsored by bodies such as DTI, EPSRC, industrial and European sources. The CPT research activity is dependent on the Ultra Precision Engineering Centre (UPEC) which contains three groups: Engineering Control and Machine Performance (ECMP) group, Gear Research (GR) group and the Surface Characterisation (SC) group.
This paper summarises part of the contribution to the public domain through research activities undertaken by these three groups over the last 10 years and up to the present day.
The ultimate goal is to produce a CNC machine tool that can control dimension, form and surface integrity to within tolerances whose limits are set by the unidirectional repeatability of the axis drives. The following sections illustrate

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the various stages of the process that need to be addressed in order to achieve this target. Heavy machining compared to light machining and precision compared to ultra precision bring different problems that must be solved.

2 High accuracy feedback transducer for single/multi-axis applications

A laser feedback transducer for high performance CNC machine tool applications has been produced as a result of collaboration between Renishaw plc and the University of Huddersfield [1]. The Helium Neon laser transducer [2] has nanometric resolution and is dedicated to motion systems requiring high speed and accuracy (e.g. manufacturing industry, CNC machine tools, robotics etc.). The transducer is now operating commercially with over 60 installations worldwide being carried out. It functions at 1m/s, but further development is underway to miniaturise the transducer and lower its cost.

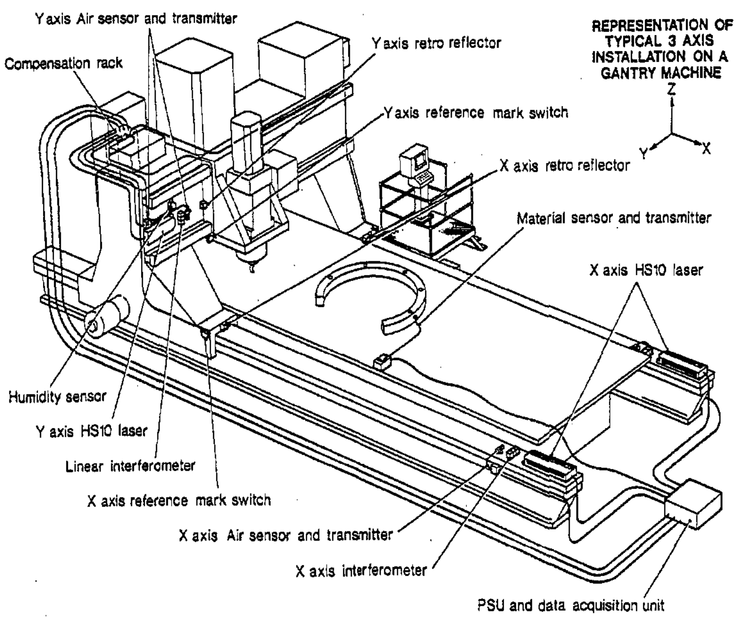

Figure 1: Laser head and measurement optics installation (courtesy of Renishaw)

The real time compensation of environment, geometric, load and thermal effects at the machine is performed by a compensation card included in the interface between the controller and transducer. The card accepts the industry standard RS485 quadrature from the laser head and generates a standard resolution compensated digital quadrature output using advanced high-speed circuitry operating in real time. The compensation software is incorporated in a personal computer and implements a novel technique for the reduction of work-piece errors caused by machine tool thermal distortion [3] and geometric and thermal measurement strategies [3, 4, 5].

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Achievements:

- The laser system allows a resolution of 0.1μm, which is commonly used, or can be configured as low as 0.079μm.
- A vertical machining centre was held within a volumetric accuracy band of 10 microns whilst the uncompensated state has a volumetric accuracy of greater than 100 microns i.e. 10:1 improvement.
- Trials were carried out on a large moving column milling machine to show before and after applied compensation (rigid body only) effects. The volumetric accuracy was reduced from 135 microns to 36 microns (4:1 improvement) [6].

3 Real time compensation of time and spatial variant errors

The accuracy of a CNC machine tool is often defined by measuring and quantifying its errors:

- geometric errors – due to mechanical imperfections and misalignments within the machine tool structure;
- thermal errors - due to changes in temperature of the machine tool structure.
- load errors – due the varying loads applied to the machine tool structure.

One aim of the EPSRC project [7] was to produce a practical real-time universal compensation system for the correction of all significant spatial and temporal systematic errors, capable of being applied to all common machine tool types and configurations. Also the system offers training /calibration procedures suitable for initialising the compensation system to machine tools and configurations within its capability class.

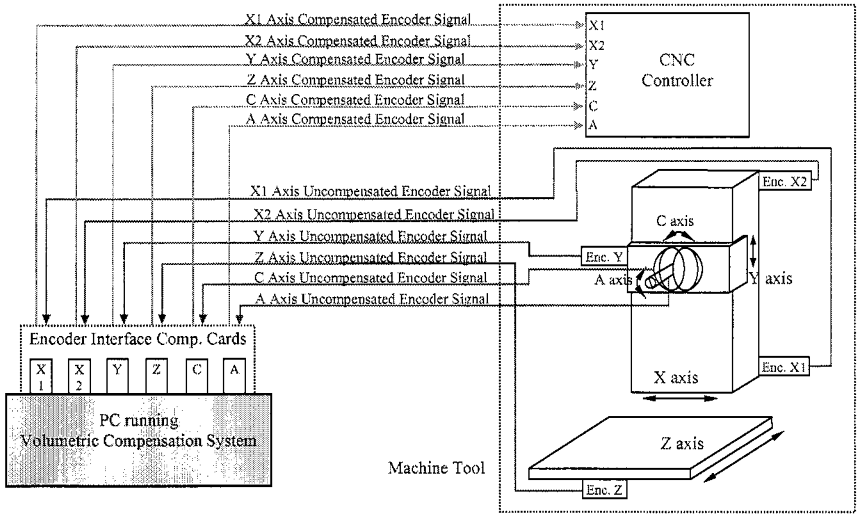

Figure 2: Volumetric compensation applied through a PC

The Volumetric Compensation System (VCS) was developed by Engineering Control and Machine Performance group. It is a method of electronically enhancing the accuracy of CNC machine tools by correcting for the linear effect of geometric and thermal errors.

The machine structure is assumed to act as a rigid body (the structure deformation does not change significantly throughout the volume). So the geometric errors measured along discrete lines are representative. The methods of implementing VCS to the machine tools are:

a) through a PC integrated in the position feedback loop of all the axes (Fig. 2) The compensation process is unseen by the controller and the system is incremental. The compensation cards in the PC intercept the pulse train of the encoders and error component for each axis is calculated based upon the current axis positions, measured error data and geometric/thermal models. Compensation is applied by adding/subtracting pulse counts to the output from the compensation cards.

b) through an OSAI series 10 controller that has the DOS Real Time Interface option installed (Figure 3). The absolute position is read from the controller and error component for each axis is calculated. The compensation is applied by updating the zero-shift offset within the controller.

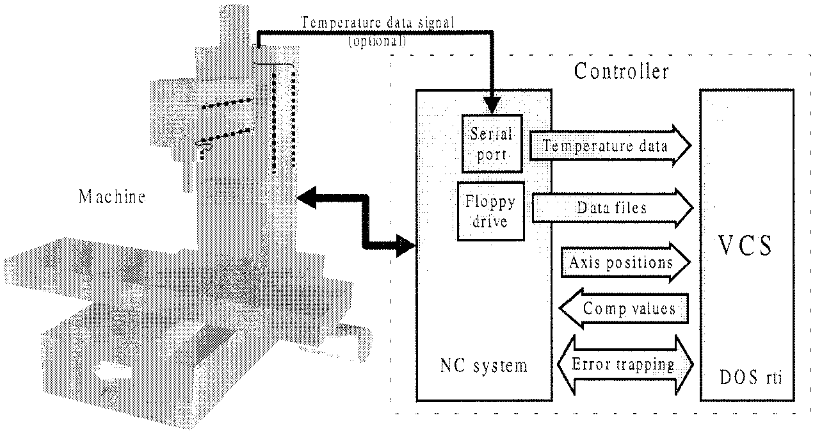

Figure 3: Volumetric compensation applied through controller

Achievements

- Full volumetric compensation for 3-axis CNC machine tools applied dynamically in 1μm steps, typically 0.2 ms update time
- The BAe/DST installations have won acclaim in the trade press [8] and commercial agreements have been reached for further installations. This work has established our reputation as a leading University in this area of research both in the UK and worldwide.
- Prof. Ford has represented the UK as a keynote speaker at 6 venues together with German and Japanese experts as a guest of the MTTA/DTI [9].

- One journal paper [3] won the IMechE Thatcher Bros. Prize on the "effects and compensation of thermal distortion".
- Validation tests on a CNC Machine Tool for correction of work-piece distortion has been shown to reduce the errors from 65 to 2 microns (32. 5: 1 improvement).
- A validation test on a machine tool temperature-based compensation system reduced head-slide thermal errors from 75 to 8 microns (9.3:1 improvement).

The research provided generic information for use by five CNC control manufacturers, eight machine tool builders, three end users, two drive manufacturers, and four transducer/instrument manufacturers. The techniques would equally apply to other large machines (e.g. Co-ordinate Measuring Machines) using closed loop position control systems.

A strategy to improve the manufacturing process capability was developed and implemented through a Teaching Company Scheme between the University of Huddersfield and Micro Metalsmiths [10]. This included automatic in-cycle time and spatial error compensation of CNC machine tools and established condition and tool wear monitoring practices to being introduced to the Company. Also a structured measurement strategy [4] was successfully used to identify the non-rigid effects on a number of different machines (see Table 1).

Table 1. Non-rigid measurement summary - change in magnitudes

Component	*Machine A*	*Machine B*	*Machine C*	*Machine D*
X linear	50 μm	7μm	90μm	Negligible
X pitch	13 arc s	3 arc s	Negligible	Negligible
X Yaw	Negligible	Negligible	Negligible	Negligible
X roll	2.5 arc s	Negligible	4 arc s	Negligible
Y linear	5 μm	Negligible	12μm	Negligible
Y pitch	3 arc s	Negligible	4 arc s	Negligible
Y yaw	3 arc s	6 arc s	Negligible	Negligible
Y roll	12 arc s	Negligible	5 arc s	Negligible
Z linear	Negligible	Negligible	Not measured	Not measured
Z pitch	Negligible	Negligible	Not measured	Not measured
Z yaw	Negligible	Negligible	Not measured	Not measured
Z roll	Not measured	Not measured	Not measured	Not measured

NB, Negligible in the above table means the non-rigid effect was indistinguishable from the measured repeatability.

Achievements

- The condition monitoring system was developed to be portable, such that the system could be linked to all machine types and configurations.
- The manufacturing strategy allowed the industrial collaborator to improve its process capability, reduce manning levels, and enable the production of parts to be completed without scrap.
- The technology transferred from University of Huddersfield to industrial company included the first known UK pre-calibrated compensation system for the correction of geometric, load and thermal errors [10] to be integrated to a CNC machine tool.

The aims and objectives were achieved and the practices have been introduced successfully into the Company. The project was awarded a grade 1 (Excellent) which is the highest award possible.

In addition to the 3-axis compensation, VCS is able to correct for errors in a two-axis servo head (Figure 4). The errors manifest themselves as a function of tool length. The compensation is achieved by resolving the head errors in the Cartesian axis directions and applying correction to the Cartesian axes [12].
The compensation systems applied to a large 5-axis horizontal-spindle machining centre reduced the volumetric error from 200 microns to 27 microns (circa 7. 5: 1 improvement) [7, 11].
Research work is still ongoing into compensation for different head configurations and agreements have been reached with the collaborators to integrate the technology to their range of machines.

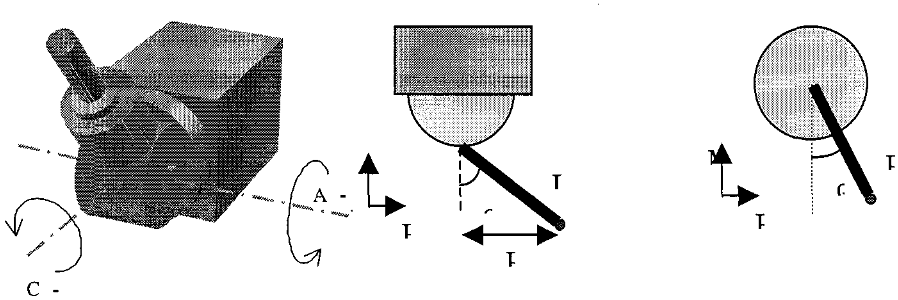

Figure 4: Geometrics of a two-axis servo head

4 Geometric error simulation and analysis software

Knowledge of a machine's volumetric accuracy provides a direct indication of its production capability, which is essentially what most machine users wish to know. It also provides machine tool users with a better understanding of the effects of geometric errors, potentially giving a better diagnostic and maintenance capability.
Until the early 1990's most national and international standards only covered axis linear positioning. The progression of standards to include measurement and analysis of axis straightness and angular errors is recognition that machine tool accuracy is a function of all the axis geometric components.

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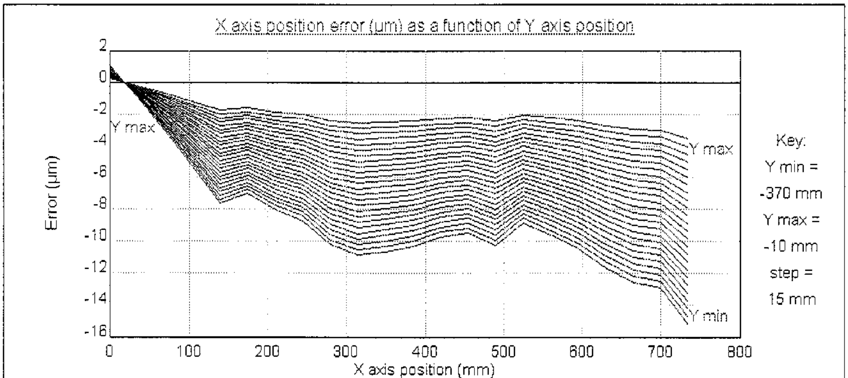
The geometric error simulation program (ESP) is designed to work with standard *Renishaw* data files and interprets linear, straightness and angular errors. The program is available in versions to run under either 16- or 32- bit Windows operating systems. A measure of the volumetric accuracy of the machine [13] is calculated from the geometric error data supplied. The effect of individual geometric errors on the overall accuracy of the machine can be calculated and displayed in a number of formats (Figure 5).



M/c:My Machine	Ser.No:Demo1	Loc:Workshop	Date:nov 98
Source:Xyaw.rta - X axis angular error about the Z axis			By:Me
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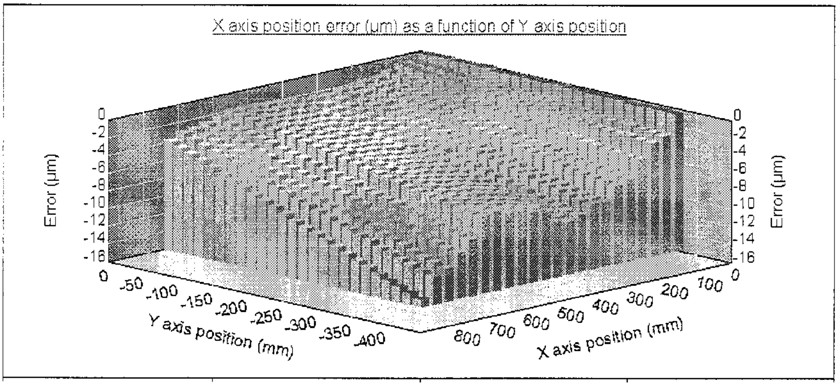

Figure 5: Displaying formats for geometric errors used by ESP

ESP uses geometric algorithms to predict the volumetric performance of a machine throughout its working volume. The system has proved both effective and reliable and has been improved by the research performed for two European CRAFT projects [14].

5 Vibration – measurement and correction

Modal tests were performed on CNC machine tools to determine the modal parameters (natural frequencies, damping factors, and mode shapes) [15]. Random excitation applied to the spindle via the dummy cutter and the stinger with Hanning windowing and the global curve fitting method was able to filter out computational modes obtained by the local method. The modes of vibration are comparable with those obtained by a specialised measurement company at one industrial collaborator site. The next step will be to build a mathematical model for vibration prediction using force measurement and structural Finite Element approach [16].

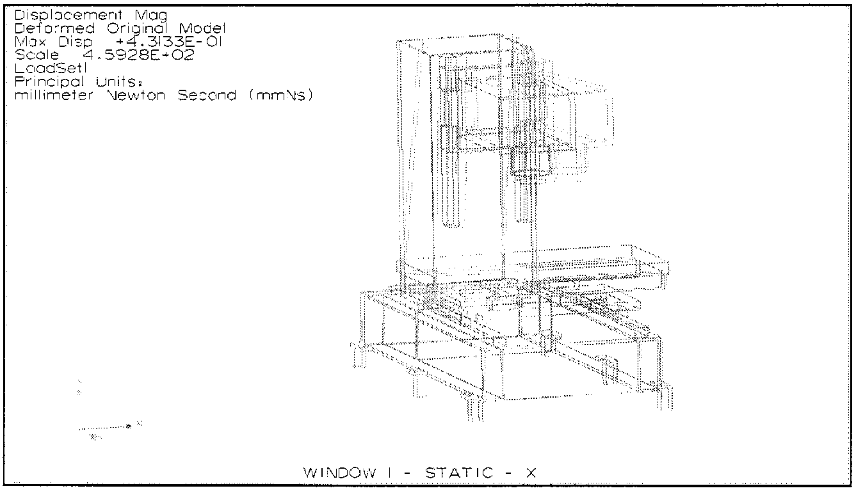

Figure 6: Deflection due to load in the X-direction

An investigation into adaptive digital filter algorithms has been performed in order to describe the time-variant nature of machine structures when cutting [17]. The adaptive algorithms will be implemented on an active base mounted under the work-piece for the active compensation of vibration. The base contains piezo-electric actuators to correct vibration in two orthogonal directions. A test rig is designed to show the potential of this approach and the results of experimental static tests are encouraging [18]. The next step will be the integration of the actuator system with a high bandwidth to a milling machine and testing the adaptive controller on the real machines.

6 Advanced compensation of geometric, load and thermal effects on CNC machine tools

The three main areas to consider for lack of accuracy on a machined component are the physical accuracy of the machine, user effects, and the work-piece environment. Research into the operation of any high precision CNC machine tool in order to achieve an ever increasing demand for greater accuracy and

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therefore a more stringent performance specification must embrace error avoidance, error measurement and error correction. The research carried out [19] was to investigate "state of the art" practices and provide a generic guide to the machine tool builders and end users on techniques to improve high performance by applying optimised volumetric accuracy correction. In order to achieve this, we had to examine the static and dynamic performance, and quantify the constituent errors for each structural element of the CNC machine tool.

Achievements

- VCS has been developed further [20] allowing the interaction with PLC to obtain information on status of compensation system and includes PLC-based watchdog. Also it interacts with CNC to obtain axes positions and apply ramp compensation to avoid standstill errors.
- The new version of the Compensation Utilities software calculates only unidirectional static error data from time-based dynamic position data. It converts two dynamic runs to static errors and correlates them with a normal static run of normal spatial resolution. Also the software creates a dynamic compensation file successfully included in VCS and the measurement time is not significantly increased, but substantial accuracy improvements on machine with high cyclic error are obtained.
- Thermal compensation was successfully integrated in VCS [21].

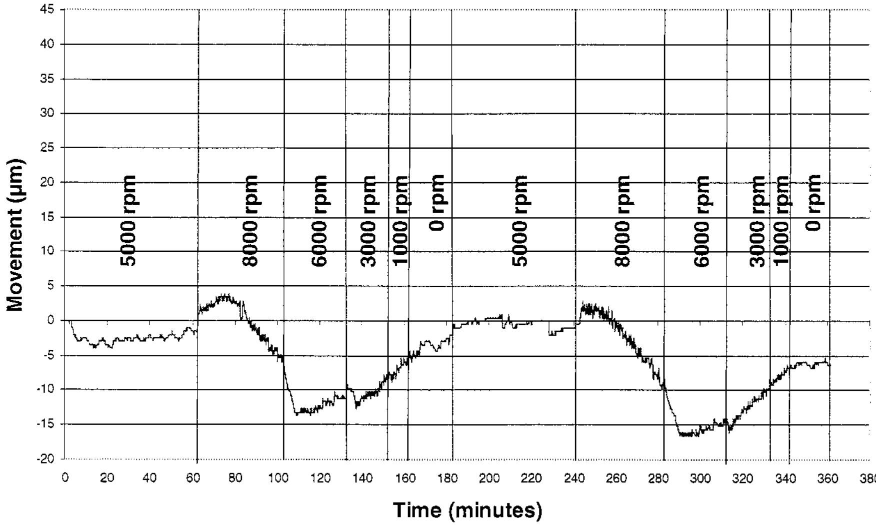

Figure 7: Measurement spindle boss movement with compensation during random duty cycle (uncorrected for ambient temperature change)

- A ball-screw thermal model [22, 23] incorporating heat sources and heat transmission within the ball-screw system, detailed information about the ball-screw structural elements and running conditions to simulate heat

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generation and position error on the test rig was developed. Its parameters include all heat transfer mechanisms and require optimisation based on temperature data taken during a typical duty cycle. Average ball-screw temperature in a model can indicate a level of pre-tension and therefore friction torque and heat generation.

- An active model considering the significant variation in the dynamic characteristics of a ball-screw system as the nut moves along the screw was built [24]. The simulation results compare well with the measured ones, but more research has to be performed in order to make the model predict more accurately the dynamics of practical ball-screw systems.

The research is ongoing and it will help our industrial partners (machine tool builders, component suppliers and end users) to improve their performance during applications for milling, turning, and grinding operations.

7 Dimension, form and surface integrity

A collaboration between two groups of CPT (ECMP and SC groups) and Leeds Metropolitan University [25] has been establish in order to:

- quantify and optimise the performance of a CNC machine tool under cutting conditions, by investigating those parameters that affect dimension, form, and surface finish tolerances
- determine correction algorithms on and off-line and produce passive/active condition monitoring strategies and practices.

Its novelty lies in the combining of knowledge of these specialised research groups whose activities (Figure 8) include 'state of the art' control of those parameters affecting dimensional accuracy, form, surface finish and integrity.

This is the first known attempt to control all those parameters allowing a component to be produced automatically approaching the tolerance restrictions imposed by the machine tool axis repeatability limits and its environment. These considerations are taken into account during our research work:

- The machine dimensional accuracy is affected by static, dynamic and thermal stiffness of the machine tool structure;
- Form considerations are the result of the control system dynamic performance, which in itself is a function of the programming algorithms, drive performance, machine cutting process;
- Surface finish is a function of tool wear, vibration and isolated events.

This topic has only been considered to be feasible because of the significant progress of 3D surface characterisation, and the respective teams standing in error minimisation practices.

Achievements

- The research into cutting process effects was performed by modelling this machining process [26]. The models and their associated adaptive control techniques will be validated by developed measurement practices
- Initial experimentation using 3D autocorrelation and spectral moments for comparison with amplitude/spatial analysis was undertaken. SC group is

researching into the establishment of which 3D surface wavelet models are most suited to machine tool diagnostics and control.

- Performance measurement trials on turning and milling machines were carried out at the CPT and collaborators sites as a part of investigating error measurement and error correction strategies to achieve the desired performance specification. One of the main objectives is to determine and introduce into the process the methodology to minimise the significant errors affecting surface shape to be validated by the development of error measurement and identification techniques.

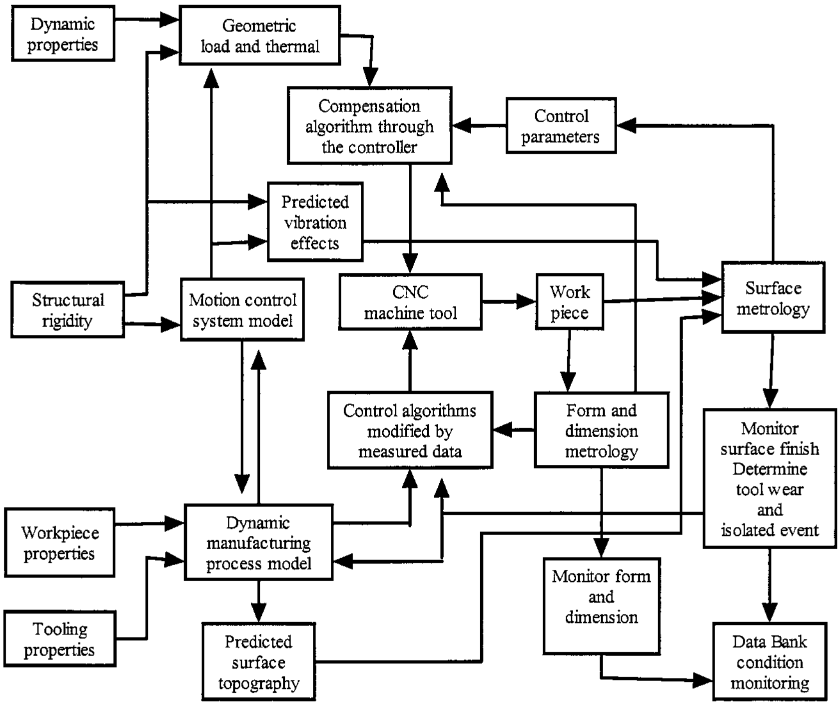

Figure 8: Activities performed by all academic partners [25]

8 Control of feed drives

To compute, predict and eliminate the instantaneous error in a precision engineering process requires computationally fast and efficient algorithms based on a mathematical model of the system replicating adequately the dynamic behaviour of the process. In particular the prediction of transient, induced stress levels, noise, vibration and wear manifest all in the final implementation which be less than optimum in terms of dynamic performance and accuracy. These problems become acute in precision engineering and metal cutting.

A non-injective method for identifying non-linear system dynamics [27] was produced with applications for machine tools, aircraft simulators, and power mills [28]. The algorithms were validated for robustness and scalability off-line and shown to be successful. However, for on-line application the research concluded that the prognosis technique would need to be implemented through parallel processing techniques. The amount of computational memory requested for on-line implementation resulted in the ECMP team concentrating on other methods for modelling the CNC machine tool feed drives.

8.1. Modelling CNC machine tools feed drives

One main aim of a research project funded by industrial collaborators [29] was to focus on modelling of CNC machine tool feed drives. A modular approach [30], [31] has been applied to overcome the shortcomings of traditional of CNC machine tool feed drives using lumped-parameter models with load inertia reflected to the motor. The authors of publications [30, 31] postulated that this technique allowed the inclusion of combined resonant states of individual elements without evaluating constituent damping factors.

However, the dynamic performance for the single axis simulation using lumped parameter models with a modular load was considered not to be sufficiently realistic when compared with the machine measured data [32]. Therefore a hybrid model of CNC machine tool feed drive with distributed load, explicit damping coefficients, backlash and friction [32] was developed. The feed drive system was modelled element by element, including for all known non-linear factors (stiffness, friction, and backlash) as identified by measurement using specialised equipment.

A schematic representation of the model for the mechanical transmission of the CNC machine tool axis drive is presented in Figure 9 when the nut is located in a central position along the length of ball-screw. The simulation results compared favourably with the measured response at the machine so the hybrid model represents to a large extent the dynamic behaviour of the feed drive.

Other achievements of the above mentioned industrial project are:

- Novel measurement practices (hardware and software) being developed for the decoding of position signals from encoders placed on the motor, ball-screw and saddle. The techniques were found to be very effective.
- Measurement strategies for the measurement on non-linear functions and salient resonant states being defined and validated.
- Stimuli signals as parameter identifiers applicable to CNC machine tool axis drive applications being clearly defined.

The ball-screw system is a non-linear dynamic system when the table is moving. ECMP group performed more research and the dynamic behaviour of a ball-screw system was modelled using a finite element approach [33]. The model takes into account the mass, stiffness and damping of a mechanical system whose configuration changes with time. A better understanding of ball-screw

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dynamics was gained through modelling process and it is hoped to use the energy dissipation features in predicting thermal behaviour of ball-screw.

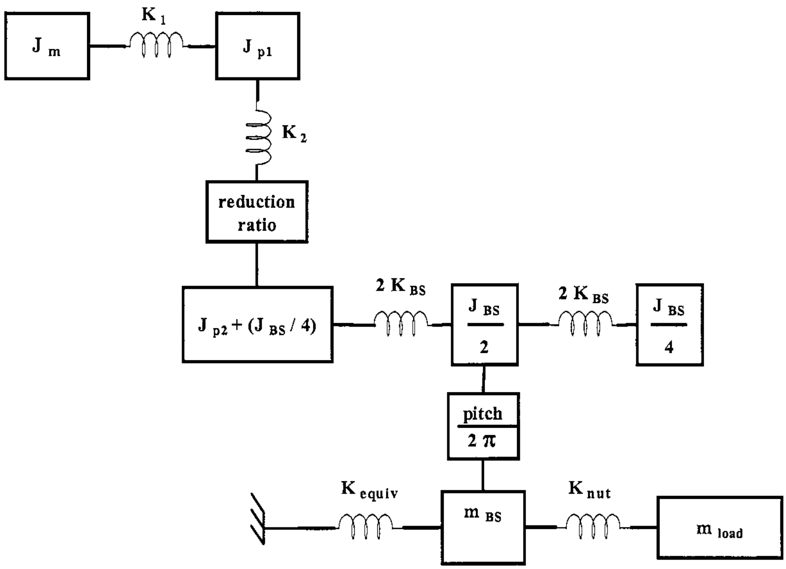

Figure 9: Schematic representation of the model for the mechanical transmission of the CNC machine tool feed drive

8.2. Modal parameter identification using wavelet transform

Another aim of the research project [29] was to investigate methods of estimating the modal parameters for the CNC machine tool feed drive elements.
A novel application of the Continuous Wavelet Transform to identify the damping coefficients and resonance states for the axis drive elements was developed [34]. The variations in the amplitude levels of weak components embedded in strong noise and non-stationary processes were detected by this method. Although in its infancy (currently it requires manual intervention), it is showing promise as an identifier.
The results are very promising and the intention is to develop an automatic identifier and algorithm for on-line parameter identification of the non-linear systems based on the wavelet transform

In order to optimise the performance of the machine tool there is a need to be able to apply robust on-line parameter identification to CNC machine tools for automatic tuning and condition monitoring purposes. It is necessary to increase the understanding of those parameters affecting dynamic performance with the purpose of achieving the end detailed modelling using hybrid techniques.
The expertise in error measurement and correction practices (ECMP group) and in hybrid modelling techniques (University of Bradford) is now combined [35] in order to achieve the following targets:

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- apply object oriented modelling methods using hybrid representations [36] to optimise the performance of CNC machine tool feed drives under non–cutting and cutting conditions;
- determine correction algorithms for geometric, load and thermal errors to be applied through a real-time compensation;
- automatic identification of those parameters affecting dynamic performance of the CNC machine tool and integration on-line to the machine to elaborate condition-monitoring methods.

CNC machine tool builders, manufacturing organisations, component/transducer/ equipment suppliers will all benefit from a successful outcome of the previous and current research. Organisations that do not require high performance, will also benefit by the improved reliability and repeatability achieved. This will enable cost effective solutions to be readily available for unmanned and de-manned installations.

5 Conclusions

The investigations to date have highlighted the need for detailed knowledge of those errors that affect machine tool performance. Our research to date has developed measurement strategies for the identification of geometric, load and thermal errors and quantification of their affect on the system.
The studies with machines of different types and configurations and detailed investigation into their constituent elements have allowed simulation packages and correction packages to be developed.
The CPT staff is now in a unique position of being able to assist industry in solving their machine process problems by offering the most cost-effective solutions.
Future research topics for consideration are:

- error minimisation applied to large and heavy cutting milling machines
- ultra precision machining
- finite element modelling of the machining process
- robust on-line parameter identification methods applied to the axis drives for automatic tuning and condition monitoring purposes

The outcomes of the research programmes could be seen as a major contribution to new knowledge in manufacturing research, facilitating collaboration between industry and academia. Therefore theses results are consistent with new Foresight guidelines.

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