SYNTHESIS REPORT

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TITLE: ***"Integration of Fiber Optic Sensors for the Monitoring of Advanced Machine-Tools " (OPTIMA)***

COORDINATOR: ***TRIMEK, S.A.***

ARTNERS: ***BRUNEL UNIV.***
3D
TEKNIKER
ISOTEST
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STARTING DATE: 01.04.93 DURATION 36 MONTHS

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ABSTRACT

*The objective of OPTIMA was to improve the overall performance of the machine tool. This includes the improvement of the quality (dimensional, superficial) of the machined parts, and the decrease of machine maintenance cost. This major objective was accompanied by a paralel objective which was to integrate signals from embedded "**intrinsec fibre-optic** sensors'! The project has run during three years and a half and has resulted in a series of technologies available for the partners. Major developments have been the fibre sensors for the measurement of temperature, vibration and force, including the electronic interface, and the software module for the compensation of thermal deformations in machine tools. Industrialized results are being exploited by the partners. Besides, the participant organisations, from Italy, United Kingdom, and Spain have obtained an important improvement in their cooperative relationships.*

1. INTRODUCTION

OPTIMA project was started in 1991 as a result of an industrial and commercial opportunity detected to introduce fibre optic sensors into the machine tool industry, for the monitoring of the quality and the performance of the machine. It is now difficult to recall which partner was the leader of the idea, but it is clear that from the beginning the joint effort of BRUNEL UNIV., TRIMEK (then MEKIFASA) and TEKNIKER was the driving force for incorporating the rest of the partners.

The partners later involved in the project joined the original idea and contributed with their aportations to the final design of the project. The proposal was focused to the development of an independent system which would be capable of predicting the quality of the machined parts, and the needs of preventive maintenance for the machine tools. The system would incorporate fibre optic sensors specially developed for the introduction in the machine tool environment.

Once the proposal was presented and accepted for finding, the consortium had to readapt their workprogramme to the approved technical memory. Furthermore, posterior counsel from the project technical auditor originated a refocus of the final objectives. Besides, the advances in software technologies, and in computer hardware during these years enabled the consortium to increase the degree of ambitiousness of some of the objectives to include the elaboration of compensation modules for the thermal deformations in the machine. Finally this aspect became one of the most relevant developments within the project. On the other hand, initially estimated schedule for the development of fibre optic sensors deemed to be too optimistic as larger efforts than expected had to be input in order to reach less than estimated obejctives. The extended period of time required for this development motivated the development of the project to be done with traditional temperature and vibration sensors.

Along the project development time, the partners have reached a high level of mutual understanding and knowledge which has caused the continuation of the relationship in fields other than the strictally research ones.

2. TECHNICAL DESCRIPTION

2.1. OBJECTIVES

Along the development of the project, since the conception to the final meeting, the main objective has been

to improve the overall performance of the machine tool. This includes the improvement of the quality (dimensional, superficial) of the machined parts, and the decrease of machine maintenance cost.

This major objective was accompanied by a paralel objective which was:
- to integrate signals from embedded "**intrinsec fibre-optic** sensors".

Other objectives stated at the beginning of the project were:

- To embed intrinsic fiber optic sensors into machine-tools.
- To establish the relationships between process parameters and performance.
- To determine the effectiveness of multivariable process control in the manufacture of discrete parts.
- To monitor process magnitudes through an integrated treatment of all the signals from the sensors.
- To improve the quality of the machined parts by means of the development of a predictive quality module, which will anticipate the final characteristics of the workpiece while the machining is being done. As a consequence, and after the proper modifications of machine parameters, a two times (200%) higher accuracy will be reached.
- To decrease the machine maintenance cost as a consequence of implementing a predictive maintenance module, which will reduce downtime and part replacement expenses up to 65%.
- To amelliorate the global productivity of the machine-tool in 30%.

All objectives were to be verified by means of a newly developed and fully integrated prototype into a machining center which would be used as test bed in coordination with a 3D coordinate measuring machine,

After the first year of project development, and mainly as a result of the conclusions extracted in *TASK 1. Sensor integration* and the recommendations of the appointed EC reviewer, the consortium decided to focus the project in a group of areas that could provide the most significant results in a short term. The consortium has focused its efforts in these selected areas during the project development. These five great areas pointed out as main objectives of OPTMA Project were:

- *Improvement of the dimensional accuracy of the machine tool.*
- *In-process roughness estimation of the part being machined.*
- *Predictive maintenance, in particular detection of lack of lubrication in the spindle gears.*
- *Interconnection of the machine quality predictive modules and the CMM (quality network).*
- *Introduction of Fibre Optic Sensors in Machine-Tool Environment.*

Even though these areas can be exploited and developed in paralell, they altogether converge in a common objective which is the **improvement of the overall performance of the machine-tool.**

2.2. STRATEGIC ASPECTS

It is possible to state and define the main strategic aspects for the **OPTIMA** Project as:

- **OPTIMA** Project results offer the possibility to ***provide value added machine-tools with no sensible extra cost for the machine.***
- **OPTIMA** Project sensors area developments, open a ***wide market for the Fibre Optic Sensors in Machine Tool Environment.***
- ***Value-Added Machine-Tools with no sensible extra cost.***

- ***Improvement of machine tools performance***

According to the last studies carried out by industrial experts for the EC [1], Machine-Tool can be characterized as a sector in a "Transitional phase", becoming a "Mature Sector", in which the innovation rate is declining, radical innovations are not being carried out and process innovations are gaining more and more significance. In fact, new competitors, such as Japanese manufacturers, are entering this market by cost advantages.

Within this context, challenges for technology management in this sector, can be found in:

- *Reduction of development, engineering and production costs,* to *survive in a growing price competitive traditional sector.*
- *Potential growth is* limited *to product areas with future technologies* like measuring/control technology, information technology, electronics and optics. This means, *to get access to new technological areas.*

A new aspect is the appearance of SMES with high levels of innovation operating in the interface between the traditional machine-tool technology and future technology areas. This strategy can be successful to avoid compiting in volume markets.

The *OPTIMA project, takes position in this context*, being an attempt to *provide value-added differential aspects to "traditional" machine-fools with the incorporation of new technologies to improve their processes and general performance.*

- ***Integration of fibre optic sensors in Machine***

The resources dedicated to research and development by the consortium in order to obtain appropriate sensors have been greater than initially expected. This have derived in the definition, design and development of a series of sensors for different magnitudes, with clear industrial application. However, currently, the introduction of the new sensors is heavily conditioned by the costs allowed by the machine-tool manufacturers. The consortium is in position to predict a successful short term introduction of fibre optic sensors in machine-tool environment, if preceded by a decided production effort from sensor manufacturing industry. Part of the development done in the project, in the area of the electronic interface for the sensors, is being successfully marketed, by the developing organisation.

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[1] "Research and Technology Management in Enterprises: issues for community policy" (Sast Project& MONITOR). October, 1993.

3. TECHNICAL DESCRIPTION AND RESULTS

In the following pages the results obtained throughout the project are explained. The chapter is divided in two main sectors. The first covers the results in the field of fibre optic sensor development while the second focuses on the thermal compensation of machine tools.

Results in the fibre optic sensor development

This section will outline the final state of the work carried out on the development of the optical fibre sensors. Previous reports have given detailed accounts of the sensor design and development process and only a summary is presented here with further progress outlined. It has been mentioned previously that the key advantages of optical fibre sensors over their more traditional electrical cousins are, primarily, their immunity to electromagnetic interference and the intrinsic safety of optical fibre links.

Each of the sensors (dimension, temperature, vibration and force) will be examined in turn and the specifications of each summarized.

Brunei Analogue Probe - 13P2

Introduction

The BP2 was primarily designed for high precision measurement on coordinate measuring machines. Analogue probes are generally acknowledged to provide higher accuracy than the more commonly used touch-trigger probes. However, current commercial analogue probes are expensive and bulky compared with touch-trigger types. The prototype described in this report provides for accuracies of one micron and is inexpensive from the manufacturing point of view. A production version would also be much smaller than the currently available types and can also be used in a trigger mode if required.

The mechanical construction is much simpler than most existing types and does not demand fine tolerances to be maintained. The simplicity derives from movements which are based on spherical polar coordinates rather than the more usual Cartesian system. Displacement detection is achieved by using an optical system which includes a fibre optic array of seven elements. The design parameters required to achieve a repeatability of I micron were determined from a complete mathematical model.

A prototype probe has been manufactured and tested. The probe can be demonstrated to prove the performance in three dimensions on an existing coordinate measuring machine.

Description of the principles

The probe design strategy was an integrated approach to three axis measurement instead of the more usual combination of three 1-D displacement transducers. This, together with a simple optical arrangement, has resulted in a compact mechanical design. The BP2 is considered to be an optimum combination of mechanics, optics and microelectronics.

The optical arrangement consists of an array of optical fibres and a concave mirror mounted on the probe stylus. The light from an infra-red source is emitted by the central fibre, reflected by the mirror and detected by the fibre array. The light intensities detected by the array are modulated by the position and orientation of the mirror, which varies with the position of the stylus.

In the probe interface unit (PIU), detailed consideration has been given to reduce the effects of noise and drift, The conditioned signals are converted to 14 bit digital signals. The incorporated single chip microprocessor finally analyses the signals rapidl y and computes the results in terms of the X, Y, Z coordinates.

Test Results

The probe prototype has been tested on a CMM (Mitutoyo model FN-503) located in the Centre for Manufacturing Metrology at Brunei University.

Sensing Direction	Omni-directional ±X, ±Y, +Z
Stylus Travel: X,Y Axes	±20 (20 mm) (See note)
Z Axis	+5mm
Measuring Range	X: ±100, Y: ±100, Z: +200 µm
Repeatability(2)	Better than 1 µm
Accuracy(2)	Better than 1 µm
Hysteresis	Not detectable on the CMM
Speed	Up to 100 positions/second
Restoring Force	15gmf (approx.)
Stylus Length	50mm
Stylus Diameter	4mm

Conclusion

A precision 3-D analog probe based upon fibre optics has been developed and tested. Due to its high precision, novel design, low cost and flexibility, the BP2 will have many advantages over existing probes, and exhibits great potential to solve many practical measurement problems in terms of accuracy, speed and flexibility. The application areas of the probe includes 3-D analogue probe and 3-D touch trigger probe on CMMs, and position sensing for machine tools and robots etc.

Temperature Sensors

Introduction

It has been shown by Tekniker that distortions caused by temperature changes are one of the most crucial elements affecting the quality of the workpiece. Modelling work has suggested that temperature sensors located at key positions can be used to monitor and compensate for these thermic fluctuations. The temperature ranges under investigation are O to 50°C and 0 to 10O°C representing environmental temperature and internal machine component temperature respectively.

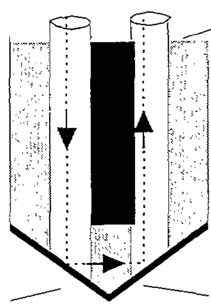
Sensor Design

After an exhaustive literature review of optical fibre methods for sensing temperature was made, certain methods were picked for further investigation. Initial work on both the microbending and Neodymium glass absorption sensors did not give promising results and these methods were dropped in favour of the gallium arsenide differential absorption sensor. The Physics behind the sensor is reasonably straightforward. When light is passed through a thin sample of semiconducting material wavelengths below a certain threshold are strongly attenuated. This is owing to the photons of lower wavelength (and, hence, higher frequency) having a high enough energy (energy is proportional to frequency) to promote electrons in the semiconductor from the valance band to the conduction band. In doing this, the photons are absorbed and light of these wavelengths does not pass through the semiconductor. The wavelength at which the photons start to be attenuated is known as the absorption edge' and it has a temperature variation which is characteristic of the material. For gallium arsenide the variation of the absorption edge with temperature is 0.35nm C-l. The longer wavelength light (with lower energy) does not get absorbed in the semiconductor and passes through the sample.

As the temperature of the semiconductor increases, the energy required from the light to promote the electrons (and, hence, be absorbed) reduces. This means that, at higher temperatures, a lower energy photon will be absorbed and the absorption edge moves up in wavelength. By monitoring the wavelengths of light transmitted through the sample of semiconductor, the temperature can be inferred.

In the practical design, the light source used was an LED emitting with a centre wavelength of 900nm and a spectral width of 50nm. Light is launched into the input optical fibre and conveyed to the sensor head where it passes through a 0.5mm thick sample of gallium arsenide. The transmitted light is returned via a second optical fibre to the receiver where the wavelength components of the light are analysed. The measurement of colour (wavelength) is a difficult procedure and it has been decided, instead, to measure the relative intensities of two particular wavelengths in the spectrum of the output light. To this end, a split photodiode (which has two photo reactive areas on a single substrate) is used in combination with two optical filters. The characteristics of the filters are that one is a narrow band- pass filter (890nm) centred around the peak wavelength of the LED output while the other is a high-pass filter (>940nm) whose cut-off wavelength falls just below the highest wavelengths in the LED spectrum.

As the temperature of the sensor changes and the absorption edge moves along the wavelength axis, the proportions of light in these filtered parts of the spectrum will vary. The amount of light transmitted by the 890nm band-pass filter is strongly affected by the sensor temperature since it is very near the absorption edge. Conversely, the high-pass filtered light does not vary with intensity very much since it lies away from the absorption edge. By taking the ratio of these intensities, a value for the temperature can be inferred. The use of an intensity ratio has the advantage that any common-mode fluctuations (particularly in the intensity of the light emitted from the source LED) will be cancelled out since it will affect both filtered intensities in the same proportion; a referenced output is achieved. The sensor design itself is shown below.



Detail of gallium arsenide differential absorption temperature sensor

A system employing 16 single channel probes was built such that one LED served 8 sensors, but each had a dedicated receiver photodiode and filter pair. It was found, after a large amount of temperature cycling tests, that there was a drift in the results which was attributed to the following causes. Firstly, the low power levels emitted from the return optical fibres. Although some 60μW of optical power is launched into the input fibre of each sensor by the LED, only between 1 μW and 2μW is transmitted by the sensor. This low power level is further reduced by the filters mounted on the receiver photodiode and the very low signal levels available to the photodiode require a large amplification. It is thought that this high amplification may introduce a small amount of noise (and, hence, error) into the system.

Temperature Drift

The largest cause of the drift, however, has been found to be attributable to the same phenomenon that is exploited in the sensor head. Just as the piece of semiconducting material in the sensor changes its optical properties as the temperature changes, so the spectral output of the source LED, a semiconductor based component, varies as its temperature changes. The LED is subjected to temperature fluctuations as a result of ambient changes as well as heating caused by the high drive current (100mA) passing through it.

It was decided that, since it is the semiconductor nature of the LED that is the cause of the drift problem, it would be useful to investigate a system which uses a different type of light source. To this end, the LED was replaced with a white light source. The output spectrum of the white light source is very different to the LED and the incandescent lamp does not have the same spectral variation with temperature as a semiconductor source.

Preliminary results from the white light source based sensor are promising. However, the use of white light has altered the response of the system considerably owing to the far greater proportion of light in the region above 940nm (i.e. the reference signal) compared to the LED source. It is thought that, with suitable further refinement, the white light based system should offer an increased repeatability over the LED version.

Concision

The achieved specifications of the temperature sensors are summarized below:

Measuring range	0°C to 100°
Accuracy	1.8*C
Resolution	0.5°C
Referencing	1.5% variation for 50% fluctuation in light level
Response time <5s	

Dimensions	2mm (diameter) x 10mm (length)
Fibre length	<12m
Drift with ambient	<0.3% $°C^{-1}$

Vibration Sensors

The vibration sensors, based on a 'black hole' displacement sensor, have been delivered and tested on the machine tool. The final specifications of the vibration sensors is given below:

Measuring range	0.1 g to 100g (acceleration) 1pm to 400pm (amplitude)
Accuracy	0.2µm
Resolution	0.1µm
Dynamic range	20Hz to 5kHz
Referencing	Compensates for <99% light source intensity variation
Dimensions	35mm x 60mm x 40mm

Although the sensor control software, as supplied, gave readings of peak vibrational amplitude and the frequency of the major component in the vibration, it is felt that a more complete frequency spectrum output would be of use. Within its dynamic range, the raw signals from the sensor do contain this frequency information and some changes of the software have been discussed with 3D to allow the full frequency characteristics to be monitored and logged.

Force sensor

Sensors are required which will measure the force applied by the cutting head of the machine during the cutting process and will be located between the headstock and the ram. A number of optically based methods for measuring force have been identified. They are: microbending, photo-elastic effect, interferometry, gratings and resonance. According to the demands of ZAYER, the sensors must be prepared to support a compression of 20x10-6 m (20 µm) without problems, measure a full range deformation of 20x10-9 m (20 nm) and with a size less then a cylinder of 10 mm in length and 20 mm in diameter. The last chosen technique employed to measure the force is based on the resonance (Triple Beam Tuning Fork-TBTF) measuring method.

Measuring principle

The TBTF is a three-beam [tines) mechanical structure. The size of the sensor is 10X 14×30 mm. Owing to the critical size of the sensor, a piezoelectric chip (PZT) is metallically attached to one of the tines to energise the TBTF (driving it to vibrate). A fibre optic displacement sensor is mounted on the same side of the tuning fork to pick up the vibration frequency of the TBTF. The vibration frequency of the TBTF depends on the tension of the TBTF which is caused by the force F applied to the sensor.

THERMAL DEFORMATION. TESTS DESCRIPTION

As indicated by the aim of the project and from the results of the task 1, the selected approach to tackle the problem of thermal deformations in the machine tools was the empiric one. Thus, a complete set of tests has been developed to study, predict and compensate the thermal effects in the milling machine object of this project. We have performed the following kind of tests, all of them performed in a real shop-floor (at the facilities of ZAYER) and under realistic conditions. We haven't employed controlled environments or thermal chambers.

The variables captured in the tests have been:

- Temperatures in different parts of the structure of the machine.
- Power in the spindle.
- Linear deformations in several points of the machine's workspace.

THERMAL TESTS CLASSIFICATION

- Test of deformation of the machine without heating. Effects due to the environmental temperature only.
- Test of deformation, heat produced by the spindle. At different speeds and in different position of the axes.
- Test of deformation, heat produced by the axes movements.

In the following sections we present the details of these tests and the results obtained from their analysis.

Elements and devices employed in the tests.

To develop the thermal deformation tests we have employed the following sensors and equipments:

- Thermoresistances PT100 class A, ±0. 15°C of precision in the O- 100"C range.
- Two TEMPULOG : Resistance to Temperature converter for PTIOO, 16 channels; provided by 3D Digital Design and Development Ltd.
- Three measurement devices, with five OMRON probes each one, to measure the three displacements and two turns of the machine in three different point of the machine in the same test. (this device was described in the deliverable 1.3). They have been provided by TRIMEK.
- Analogical data acquisition equipment for PC; 32 analogical inputs O-1 OV, 12 bit resolution.
- PC computer 80486 with MS-DOS and WINDOWS 3.1, and software for data acquisition developed by TEKNIKER.

Reference of the thermal tests performed.

In the data acquisition phase, and in order to fix data parameters of the compensation algorithm, fourteen valid tests in different periods of the year were performed. Special attention was paid to make the tests in different positions of the Y and Z axes. In this way very diverse conditions were found; allowing the future algorithms to comprise broad temperature and deformation ranges.

The description of the common characteristics of the test is as follows:

Every test was performed in a period of time that comprises day and night, thus we were able to capture data that reflects the behaviour of the machine against the changes of the environmental temperature.

In order to obtain greater variations in the deformations, a first phase of heating followed by one of cooling, was designed.

With similar objective as the reflected in the above paragraph, we don't allow an uniform heating during all the test, but we proceed with several "pulses" of different duration.

In each test, sixteen temperatures, fifteen displacements and one power were recorded each six minutes (ten samples per hour).

TESTS ANALYSIS.

The graphics of the temperatures and deformations of one of the tests are enclosed in the appendix. The first graphic contains the temperatures from T9 to T 16, that belongs to the spindle and ram. The second graph has the temperatures form T 1 to T8 that reflects the thermal field in the console, carriage, column and table. The third graphic reflects the deformations in the three axes, X Y Z in each of the three measurement positions 1, 2 and 3; thus X 1 means the deformation of the X axis in the measurement point 1, etc. Each division in the abcises axis represents a lapse of time of one hour; p.e. the sixth hour of the test begins at the mark with the number 61, etc.

In a detailed analysis of the tests we could remark:

The qualitative behaviour of the deformations of the machine follows a regular path, this suggests us some success when we will develop the empiric algorithm for compensation.

The behavoir of the temperatures of the spindle and ram could be classified into two groups: T9, TIO, T12 and T13 have a similar form; T11, T14, T15 and T16 follow other pattern. As commented in the deliverable D3.2 "Set of rules for in-process quality determination. Effects of variable modifications into final overall quality", this causes a "strange" effect on the deformations of the X and Z axes.

The repercussion of the environmental temperature is remarkable; small variations of temperature due to the switching on and off of the ZAYER'S shop-floor heaters cause deformations up to 20 microns (see in p. A2-3 the ripply that suffers the deformations of the X and Y axes at the end of the test. Also this ripply could be seen in the sensor T11).

A difference of temperature in the environment of 3°C causes an important deformation in the machine: X and Y axes reduce the negative value of their deformations up to 40 microns, while the deformation of the **Z** axis becomes more negative up to 30 microns, This leads us to the idea that an external increment of the temperature counteracts the effects caused by the internal heating of the machine, as expected in our hypothesis!.

- In the temperature graphics it could be seen some peaks and valleys, this is due to the non-uniform heating cycle of the testing procedure. Small variations appear clearly in the axes deformations, more neatly in the X axis.
- There are some tests in our collection that show complex sequences of heating and cooling. As it was observed in the test of the 12th of January, the temperature suffers large variations; the behaviour of the deformations seems caothic. But it can be predicted with great precision.

CONSIDERATIONS ABOUT THERMAL DEFORMATIONS.

In the development of the thermal compensation algorithms, we considered useful to begin with the qualitative analysis of the machine-tool in order to get a deeper knowledge of the thermal effects and their repercussions. But before to begin with the description of the results, we are going to enumerate the main general concerns we have found in our research.

Thermally-oriented design methods, based on the Finite Elements Method, has proved that small variations in lubrication conditions, tightness in the assembled parts, etc. cause large variations in the final results. Nevertheless, our approach is empirical and we do not try to justify theoretically every small perturbation, but to give a general overview about how the machine behaves, and how we can relate it to the readings of the temperature sensors.

An important point to be commented is that from the initial steps in the project we realise that thermal deformations is not a quantity that can be univocally defined from actual temperature readings. It depends on the past thermal states of the machine and in theory we must consider a “state space” model as the most suitable one to explain it. In the Figure it can be seen how temperature and deformation evolve. For the same temperature of sensor T9 very different Y axis deformations could be observed in the machine.

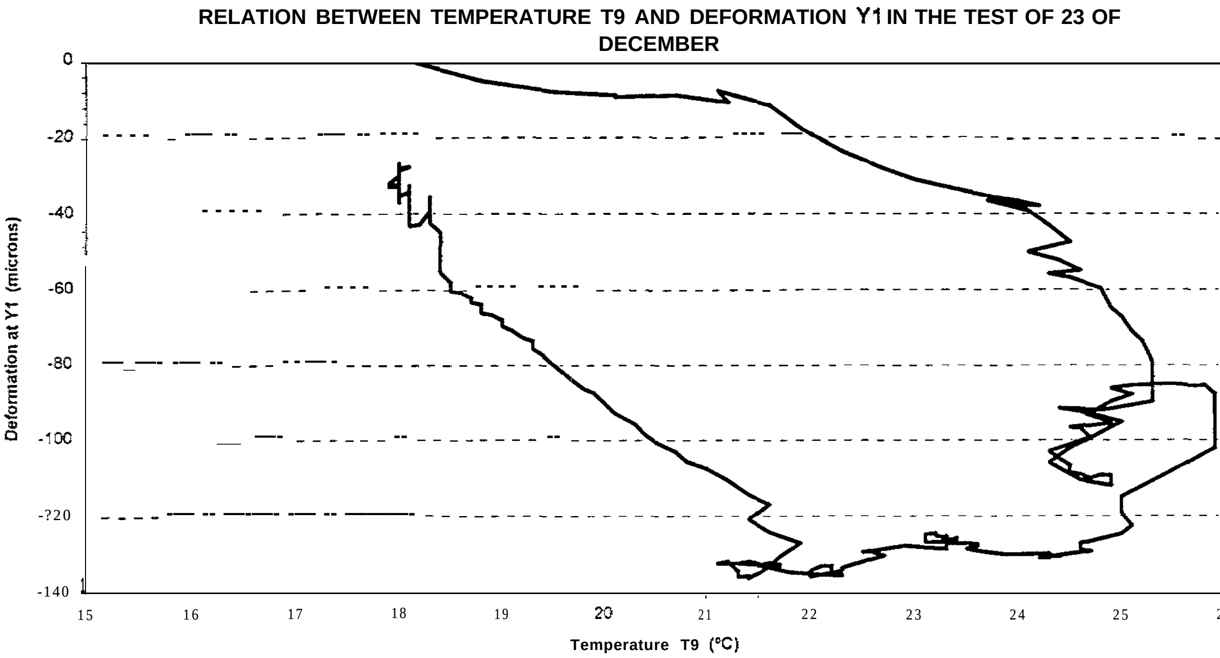


Figure 1.- **Example of non-univocal relation between temperatures and deformations.**

Different approaches can be taken into account to solve this problem. Solutions based on autoregressive temporal series, in particular ARX (autoregressive series with exogenous input variables), could be the best-fitting solution to the deformations problem; but it has a drawback, you need very accurate knowledge of the output[1] in each step of the estimation; In control processes, where this method is widely spread, this is achieved @means of measuring directly tile output variables. In our case it has not sense, if we can measure the real deformations of the machine, we can compensate them directly without the help of any algorithm. But there exists another approach that could be useful to our purposes: to enter into the model the values of past temperatures.

As the number of sensor are reduced more and more, the problem of non-linearities are greater and we must take this into account when choosing the algorithm. Neural networks are specially well suited to accomplish with task and obtain much better performances than linear algorithms such us least squares regression. Also the thermal fields of the machine behave in a non-linear way due to two main reasons:

- The heat dissipation is not proportional to the temperature due to that the parameters of convection depends on temperature.
- Researchers in heat transmission. in machine tools point out that the "thermal resistance" of the joints depends heavily on temperatures, deformations, etc. This leads to a non-linear model, and the approximation with lineal systems can be only a first approach.

[1] In our case the output is the deformation of the machine.

AH of these reasons, and the fact that we found a paradigm of neural network which accomplish with the time dependant phenomena in a graceful way lead us to employ the "Temporal backpropagation multilayer perception" as the basis for our developments.

Thus we have introduced the FIR backpropagation Neural Network as our basic algorithm to estimate deformations from temperature readings; it takes into account the temporal dependency in the thermal behaviour of the machine. This version of the neural network paradigm developed by Rumelhart and McClelland, but with the weights that interconnect neurons replaced by FIR (Finite Impulse Response) functions.

This new algorithm only needs to remember some past temperatures in order to perform a valid output. It means that you can only perform a valid compensation if the temperature of the machine has remained stable in the last one or two hours, or if you are logging the temperatures at defined intervals even when the machine is switched off. Both restrictions could be easily solved with the actual equipments. Advantages and disadvantages from the traditional algorithm and the new approach are summarized in the following table:

	Non-FIR Approach	FIR Approach
Advantages	. Simple computations. • It is not needed to store past temperatures.	• Few sensors, only one per hot point. Easy to wire, easy to maintain. • Greater accuracy as the temporal behaviour acts as it would replace sensors closed to the actual ones. • It matches very well with the real phenomena studied.
Disadvantages	• It cannot represent the temporal dependencies inherent to thermal deformations. • It needs more sensors for the same accuracy • You need to put sensor in internal structures of the machine to know the temperature field of the core of the machine. • More expensive to wire the machine and to maintain the compensation system.	• More computation needed. • It must be needed to store past temperatures (but the algorithm itself can do it). • It will suffer more from changes in the location of the sources of heat

Now we will depict the tipology of the algorithms employed in our project and how they acomplish with the desired behaviour for thermal deformations; then we give the complete reference for the algorithms and the parameters involved in them. At the end, we show the results obtained in the compensation of the milling machine.

Global algorithm structure.
One of the most relevants aspects detected in the thermal study of the machine, and refered to in the Deliverable D3. 1, is the dependence of the deformations with the position of the machine axes; the Y axis has the greater relevance is this aspect.

For our compensation purposes this means that it can provide two kinds of solutions, the first one is to consider in the same algorithm both temperatures and axes positions as inputs and provide an algorithm that generates the adequate output for the compensations in the three axes. The second possibility is to separate the influence of each factor and provide interconnected algorithms for both phenomena, the main advantages and disadvantages of each focus are summarized in the following table:

	Unique Algorithm	**Coupled Algorithms**
Advantages	• Slighty better results.	• Simple to be implemented. Simple calculations. • Real-Time compensation with the possibility to include the non-linearities provided by the Neural Networks.
Disadvantages	. Sensor fusion approach needed. • Too complex to be implemented in real-time. External hardware and coprocessor needed. . The overall complexity increases as the number of influent axes increase.	• - .

In our project **we** have choosen the second option. We have provided two algorithms, one based on FIR neural networks and other based in linear regression.

In the neural network algorithm we have implemented the dependence of deformations with the thermal field of the machine. This means that for a selected point in the workspace of the machine we have estimated the expected deformations taking into account only the temperatures at the different sensors. This algorithm doesn't need to run in real time due to the changes in the temperatures evolve slowly. Actually it is implemented in a PC under Windows 3.11 but in a near future it could be implemented in CNCs (To implement a Neural Network, the only requirements for a CNC/PLC is that it must support customer programming capabilities in background, a moderate storage (4-8 Kb) free for the user, and the possibility to work with a programming language that allows indexed and/or indirect addressing (arrays and/or pointers to variables) and flow control for the programming (loops, jumps, etc.). Actually most of the CNC/PLCs in the medium and high ranges support these functionalities, and in the very near future the low cost CNCs also support them.

The linear regression algorithm is based on the real deformations measured at different positions along each axis, all of them at the same time, and thus with the same thermal field. This algorithm allows, knowing the deformations at one point, to extend them to other different points of the machine. It can run in real-time because the calculations needed to affect the values of the deformations with the axis position only implies a few multiplications and adds. The overall phisical and logical architectures are reflected in the Figure 2 and Figure 3 in the two following pages.

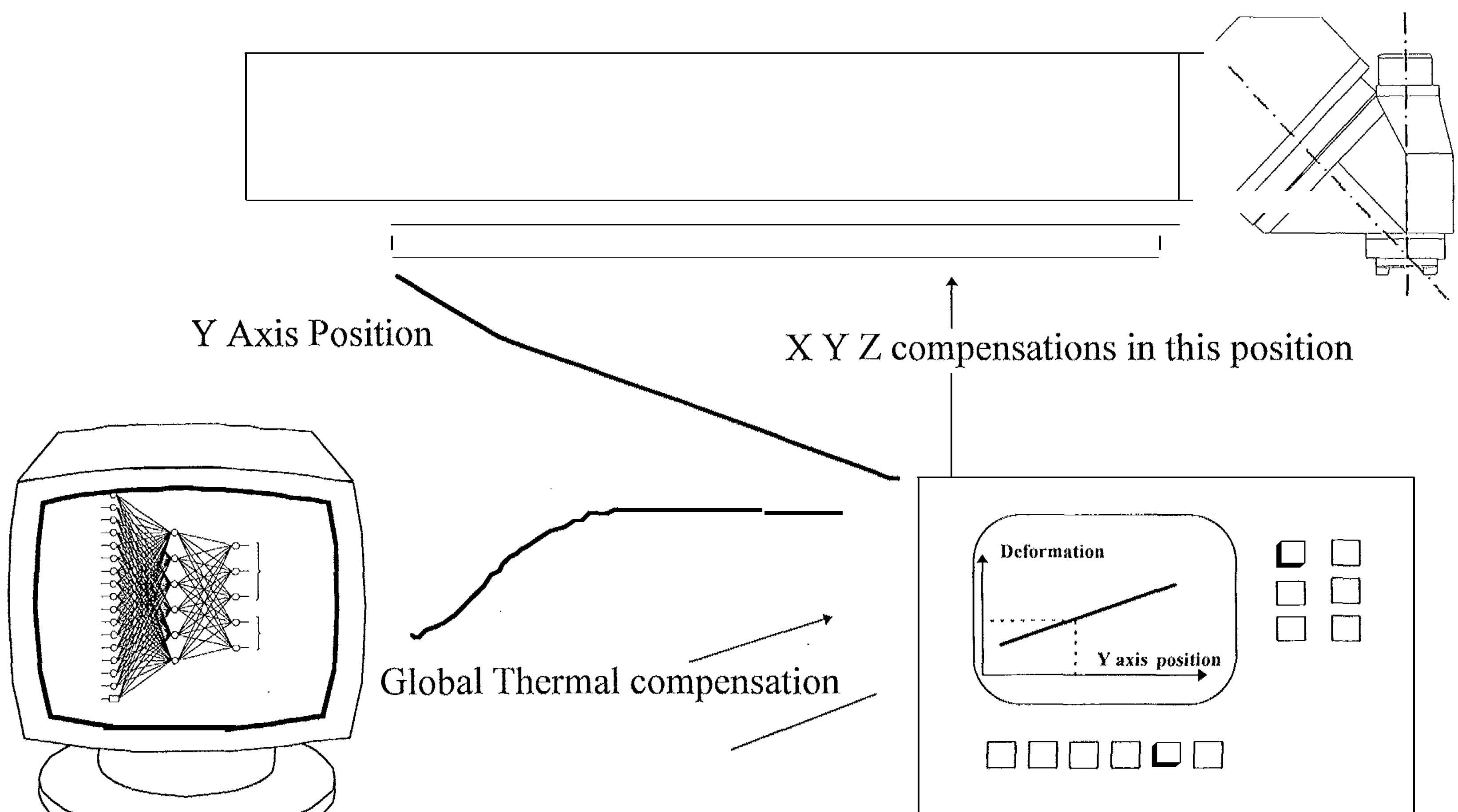


Figure 2.- ~~Physical architecture~~ **of the compensation system.**

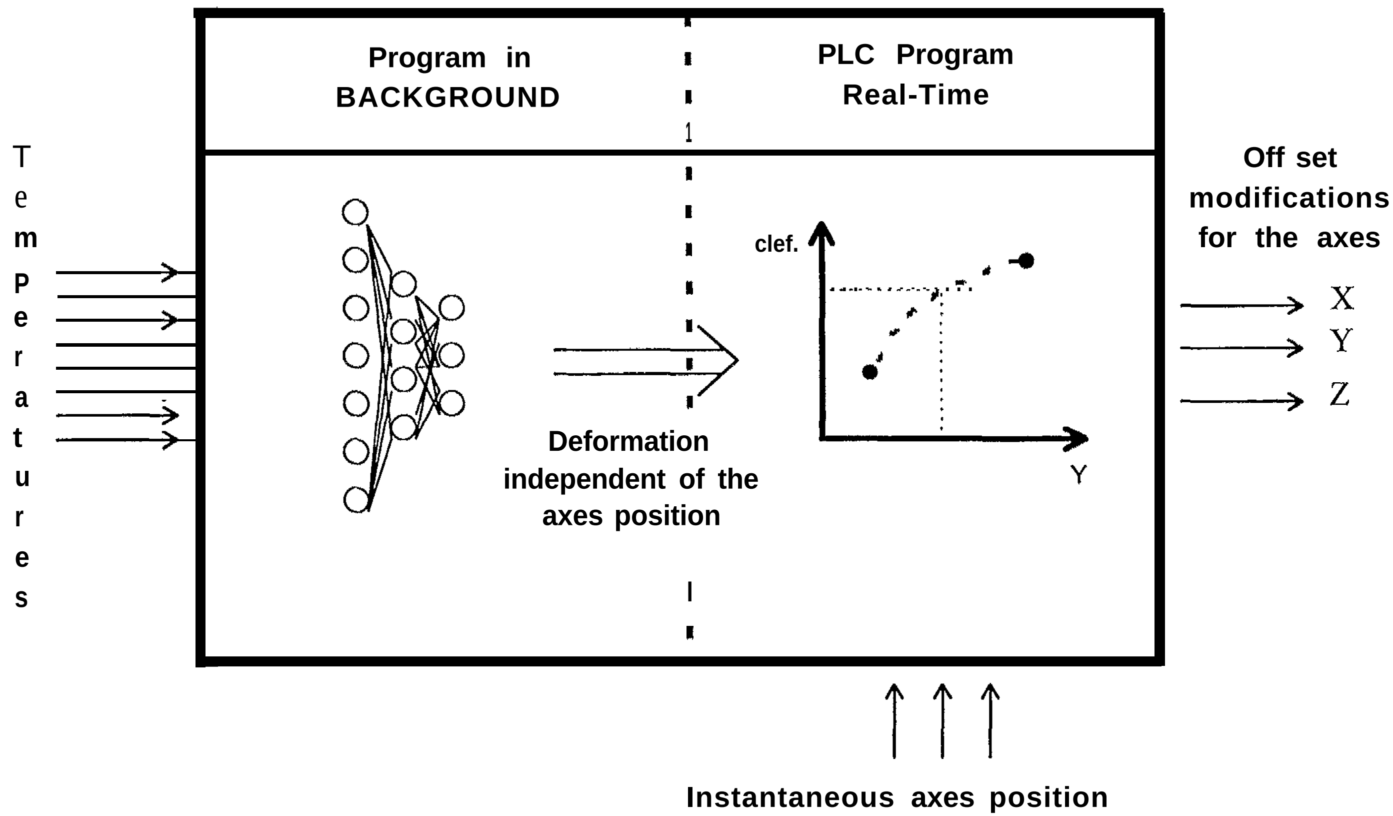


Figure 3.- Software design of the compensation system.

Compensations obtained for thermal deformations.

In order to know the expected performance of the algorithms we trained the neural network and then test the accuracy of the estimations. We made it in two difference forms. First we made a large study by cross-validation and then we divide the data in training and test sets and obtain again new encouraging results.

The most representative data are obtained by cross-validation. With this technique we train the algorithm employing all the data but the employed in the test phase. In our case we have eleven files with the data recorded {sixteen temperatures and fifteen deformations); in each phase we employ ten of the files to estimate the model and the other file to evaluate the performance of the algorithm. We have repeated this procedure eleven times changing the test file.

In Figure 4 and, Figure 5 it can be seen the graphical results of some of these predictions, In black lines are represented the real deformations, in grayed lines it appears the predictions of the deformations. The spacing in the abcises axis represents ten units per hour. The global results of

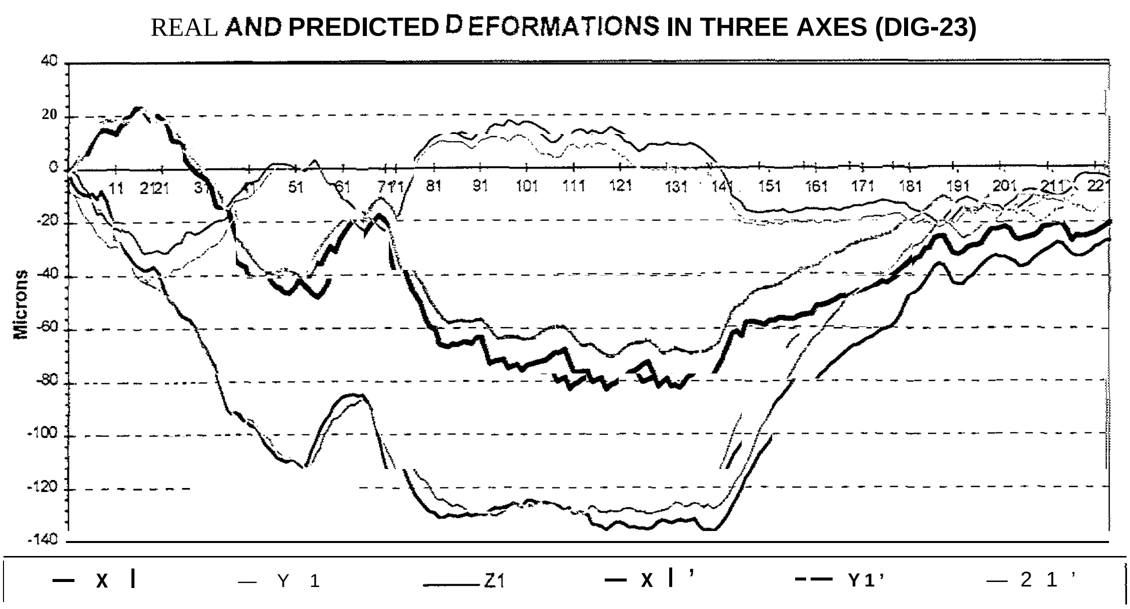


Figure 4.- Real and estimated deformations for the test Die-23. Data from Die-23 was not employed to fit this model

the compensation are quite satisfactory.

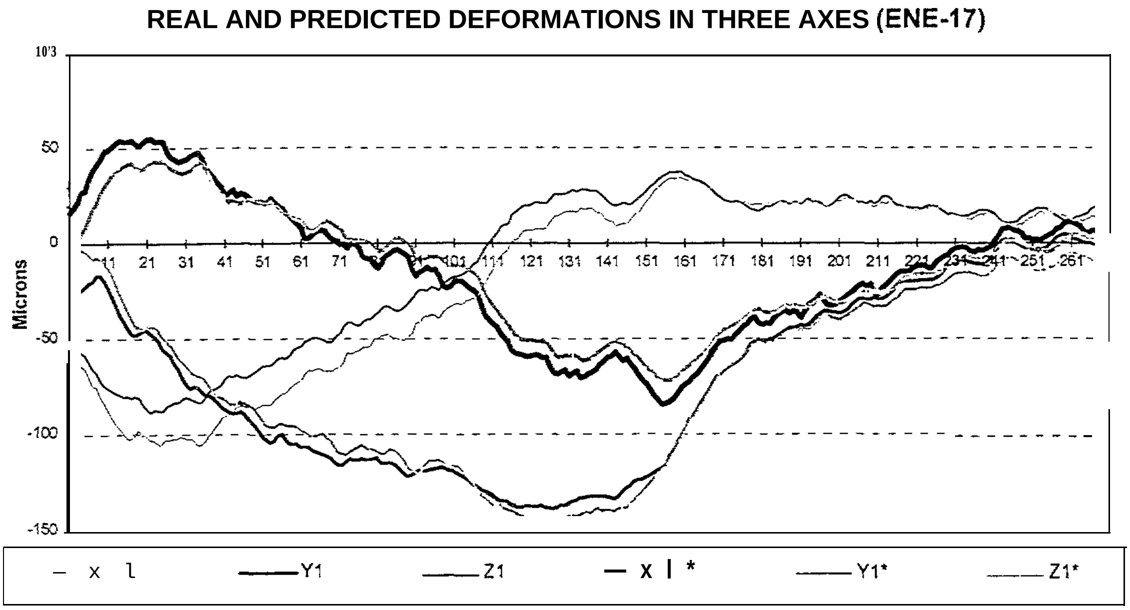


Figure 5.- Real and estimated deformations for the test ene-17. Data from ene-17 was not employed to fit this model.

3.- OVERALL CONCLUSION

The overall conclusion is necessarily positive, as the project has served to obtain practical results based on technological development, some for immediate use as the case of the software algorithms and the DSP electronic interface, others for medium term exploitation as the temperature and force fibre sensors.

It has also served to improve the cooperation activities among partners in three different Member States, which already maintain business relationships[1].

Technical performance of the partners has also been improved thanks to the project[2], and personnel in the research organisations have deepened in their research areas,
Several researchers have participated in the development in BRUNEL and TEKNIKER, and the research lines have been strengthened. A Brite/EuRam project has been derived and recently started by TEKNIKER and ZAYER in the field of thermal behaviour of machine tools.

4.- ACKNOWLEDGEMENTS

This project could not have taken place without the decisive support from the European Commision, and particularly from the Brite/EuRam programme (EC DGXII), within which it has been approved as project number 5251, under contract number BRE2 CT92 0183.

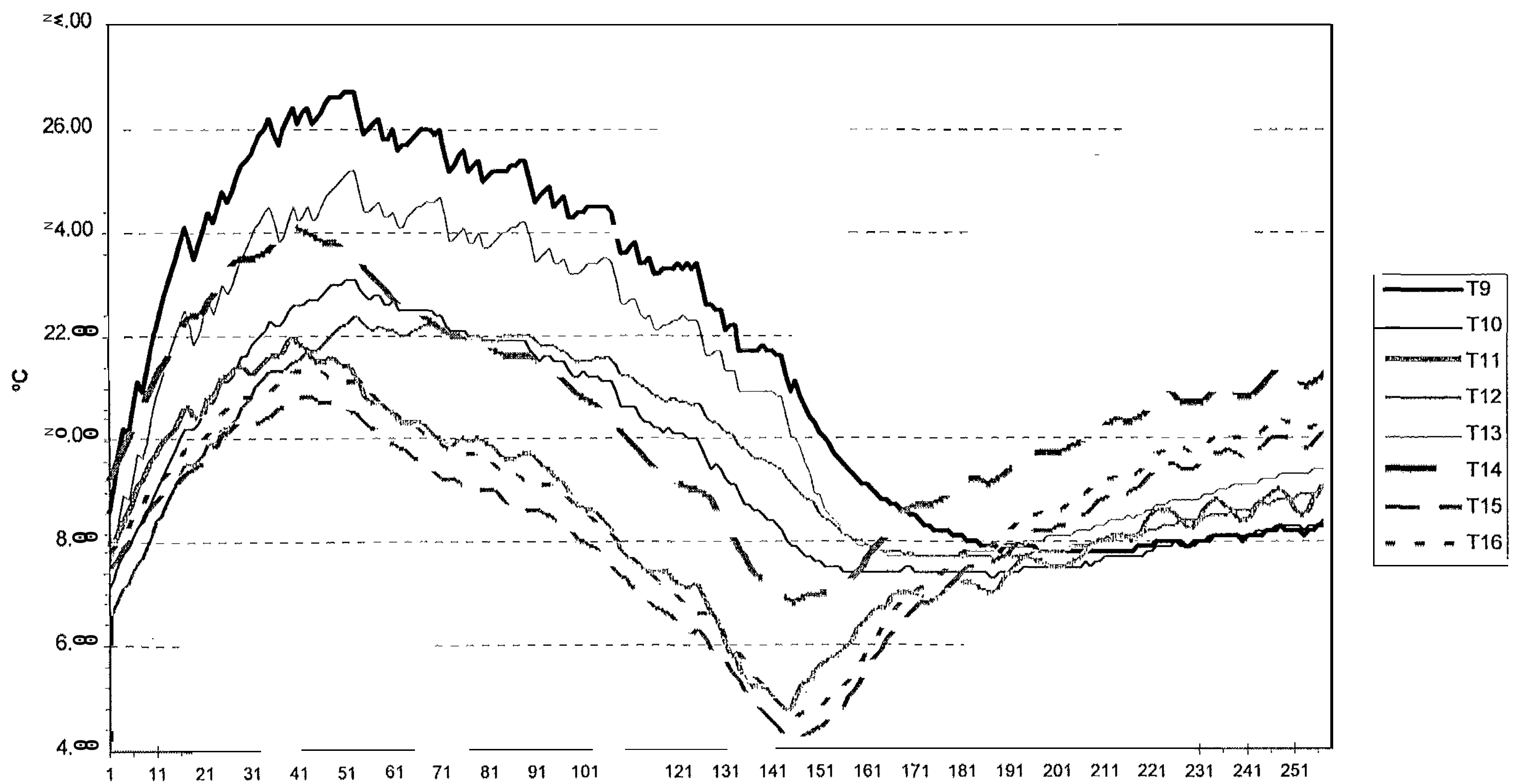
The partners appreciate their collaboration and that from Mr. Maurice CHEVALIER, who has acted as an involved project assesor.

The partners also thank the SPRI agency from the Basque Government for allowing the presentation of the project results along the International Machine Tool Exhibition in Bilbao, in March 1996.

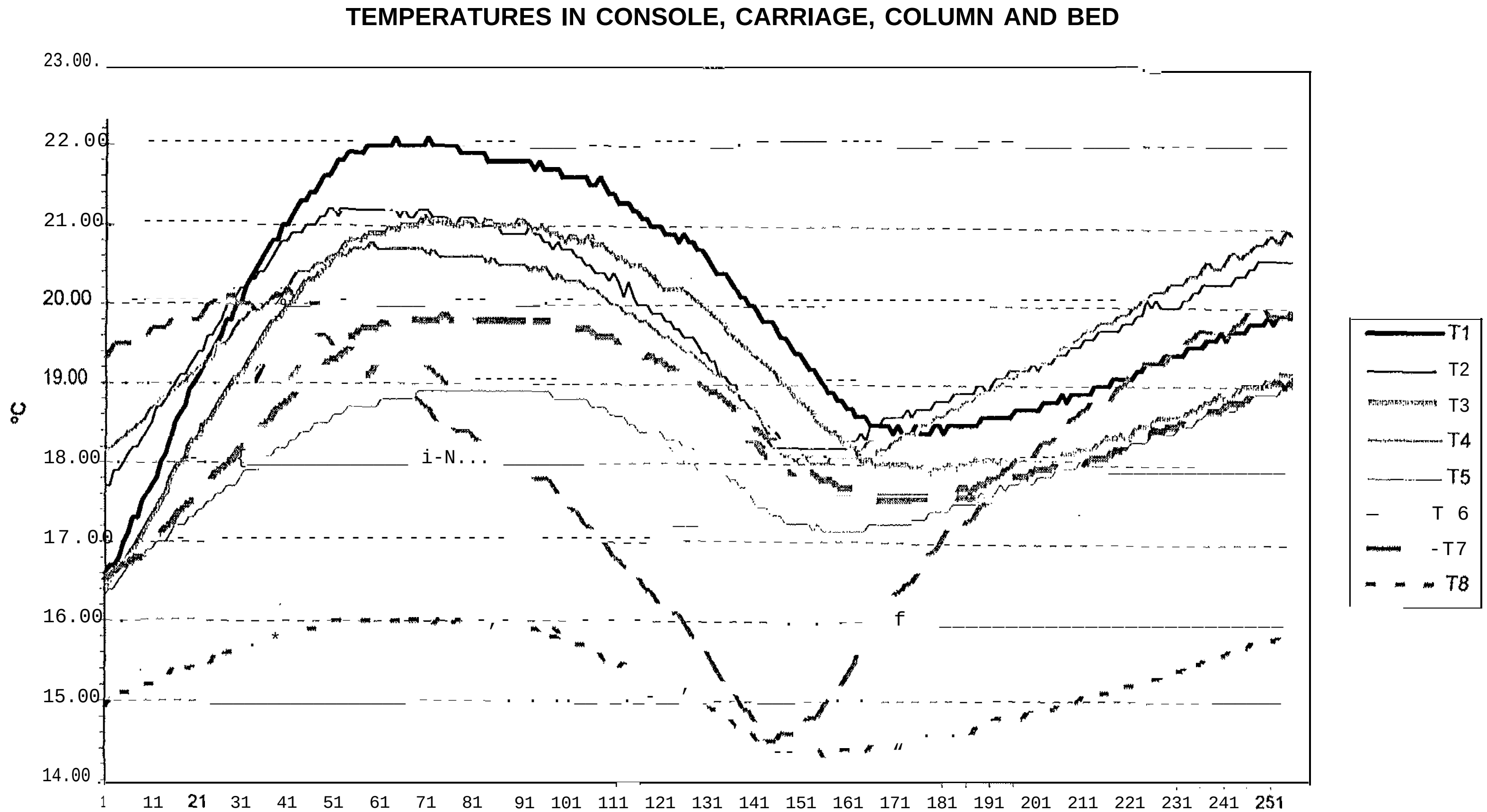
[1] ISOTEST has already sold some of its equipment in Spain, and is on the other hand counting with 3D to develop part of their electronic interfaces, as so does TRIMEK.
[2] TRIMEK has employed the knowledge from the behaviour of the machine to improve their machines, with no extra production cost, and has received an order from General Motors (USA) for fourten CMM in 1996.

A2.4.- Temperature in the spindle and in the ram. January 3rd

TEMPERATURES IN HEADSTOCK AND RAM



A2.5.- **Temperature in the console, carriage, column and bed. January 3rd.**



A2.6.- Deformations in the three measurement positions. January 3rd