Executive Summary:

Machine tools are a key component in industrial production processes, as they provide an important contribution to the added value of manufactured products. They have evolved from purely mechanical structures with manual driving to electric drives and currently electronically controlled by a CNC in order to achieve the required performances for several machining processes. The relatively recent irruption of mechatronic concepts, which take advantage of the incorporation of active devices and certain degree of intelligence into the mechanical structures, allowed to break limits and provided increased performances to the basic mechanical structures and hence to machine tools.

The present project proposes a new approach in the exploitation of active intelligent devices integrated into machine tools. The main idea is to equip a machine tool with a variety of active intelligent devices, which would be intelligently activated and parameterized in order to change the overall configuration and performances. This way, the machine would be rapidly configured to the different and even conflicting conditions or performances required for the target machining operations.

The intelligent devices are grouped in four sets:

Headstock: The spindle is a main component of the machine tool, and one of the parts of the machine with the lowest reliability. Research is conducted towards developing a new generation of spindles based on magnetic bearings, able to provide extremely high speed, power, and damping, to get rid of the maintenance required by the conventional rolling bearings. A further development consists in using the displacement capability of the magnetic bearings to correct the contouring errors produced at the drive axes. At the same time, a modular device able to transmit axial vibration to the tool was developed. By means of it, long chip production, and its corresponding problems, is avoided, and it is possible to mill hard materials in a conventional machine.

Structures: The goal is to increase machining accuracy and productivity by issues regarding the structural behaviour: Structural vibration, Static deformations, and limitations in dynamics of the drive axes. By the developed gadgets, static deformation can be compensated, and damping can be given to the structrure by different means, giving rise to a more stable, more precise, and less vibration prone, machine.

Workholding: It is intended to develop systems that ease the process of locating the raw part in the machine. This is a difficult problem, because the excess material of the raw part has to be balanced, so that there is enough material to machine at all the surfaces. The development permits the characterisation of the excess material of the raw part, and its comparison with the design. Then, the location of the raw part is obtained in an automatic way via verification by means of optical systems.

Control: More and more mechatronic systems are used in machine tools, including the devices developed in this project. The selection of the parameters for them, as well as their activation or deactivation depending on the work that is being performed is becoming more and more complicated. An intelligent control system was developed, able to learn from

experience and to interact with the user, with the aim of using the best possible conditions for each machining work being performed

Project Context and Objectives:

Machine tools are a key component in industrial production processes as they provide an important contribution to the added value of manufactured products. They are based on mechanical structures conceived as a result of optimised designs in order to achieve the required performances for each one of the machining processes.

The relatively recent irruption of mechatronic concepts, which take advantage of the incorporation of active devices and certain degree of 'intelligence' to the mechanical structures, allowed to break limits and provide increased performances to the base mechanical structures and, hence, to machine tools.

The present project proposes a new approach in the exploitation of active intelligent devices integrated in machine tools. The main idea is to equip a machine tool with a variety of active intelligent devices, which would be intelligently activated and parameterised in order to change the overall configuration and performances. This way, the machine would be rapidly configured to the different and even conflicting conditions or performances required for the target machining operation (e. g. roughing operation on steel, requiring a stiff machine versus high speed machining on aluminium, which requires a light, highly dynamic machine).

As a result of this approach, a base mechanical structure equipped with an assortment of intelligent devices could be configured as a different machine depending on the selected gadgets, so that the resulting characteristics and performances of the machine could be adapted to those required by each particular machining operation, that is, a chameleon-like machine tool concept.

The main objective of the project is to develop a new concept of machine tool so that it is completely configurable and adaptive, based in mechatronic devices, in order to cope with multiple and even opposed requirements of the machining operations.

More information on the project can be found in its website: http://www.chameleonproject.eu/

The project has 4 development Workpackages, compiling respectively developments on the head, structures, fixturing, and intelligent control system.

WP1 ADAPTRONIC HEAD

Spindle head is one of the most critical elements of current high performance machine tools. Rolling bearings are the weakest part of high speed spindles, as well as of the complete machine. They are fragile, their life is limited and very sensitive to collisions, and the replacement of the bearings is delicate and expensive.

Magnetic bearings introduce some advantages to this kind of spindles, such as longer life, quieter operation, impact detection, and the possibility of physical signal estimation (such as cutting forces, linear accelerations). Accuracy of the machined part can be improved, due to a more accurate rotation of the spindle and the possibility of avoiding the transmission of the unbalance forces to the machine structure.

The most interesting performance of these spindles is the availability of a large number of signals, which can be used for a number of different purposes, and the possibility to adapt the behaviour by modifying the control system of the bearings.

At the same time, cutting hard, fragile materials is a big issue, and during the last years it was shown that ultrasonic vibration helps obtaining better results. Application of that technology was done either on especially built machines, or by piezoelectric drives holding a static tool, like in a lathe. In this project one of the aims is the development an interchangeable device able to provide ultrasonic vibration in rotatory tools, like millls. In this way, any milling machine or machining center could benefit from the capacity of dealing with hard, fragile materials.

WP2 ADAPTRONIC STRUCTURE

The mechanical structure of the machine tools is their basic component and provides some of the key characteristics to their performances. In this work line the project deals with the adaptronic concept of these, in many cases huge mechanical structures.

The performance that can be obtained from the structures can be optimised, but in all cases have some limitations due to availability of materials, cost, etc. It is more and more frequent that the performance of the complete machine is limited by the performance of the structures. Chameleon will deal with adaptronic techniques able to compensate for these limitations.

The aspects that will be developed will be: Active error compensation (compensation of static and dynamic deformations by active systems), Rapid calibration (a system for calibrating the machine in an absolute coordinate system, able to be integrated in the machine itself), Active damping (an inertial magnetic two-dimensional actuator, able to increase the chatter free cutting capacity of the machine), and Active filtering (a filter system able to adapt to the variable conditions of the machine, and working independent of the CNC).

WP3: ADAPTRONIC WORK HOLDING DEVICES

The aim of this workpackage is to develop gadgets to facilitate the positioning of the workpiece in the machine. The problems to address are:

- Location of raw parts so that the machinings to be performed will find material along all the machined surface => Raw-part Inspection.
- Development of a system of fiducials and the corresponding sensing equipment, in order to locate the part accurately in the new settings after the first machining operations => Fiducials.

- Fixating the part in an accurate, automatic way, to easily obtain the right orientation, and avoid deformations of flexible parts => Intelligent fixtures.

Raw-part inspection

Raw parts to be machined usually come from casting or welding. Commonly, they do not have appropriate reference geometries to fix them on the machine.

The solution chosen to automatize this process uses photogrammetry to characterise the geometry of the surfaces to machine. Transferring the raw part into the final part using a mathematical approach to assure that there is excess material at all the measured points provides the reference system to centre the part in the machine in a sufficiently accurate way.

Fiducials locating system

Fiducials are geometrical features that can be easily and accurately be located. Fiducials like accurate holes, surfaces, etc. have been extensively used as a way to locate the part with precision, or to correct occurring machine distortions.

The aim of the task is to develop a set of fiducials and the corresponding sensing system. The goal is to locate the fiducials in its three coordinates, so that an standardised methodology can by applied to calculate the location of the axes of the part in the new setting.

Intelligent fixtures

Fixtures are workholding devices used to establish and maintain the position and orientation of a workpiece in a machining operation. Intelligent fixtures go beyond traditional fixtures by self-adapting to manufacturing process conditions. A modular design will make it possible to adapt the fixture for different clamping tasks.

An essential property of the intelligent workholding device is the feasibility to align the work in a automatically way. The alignment goal is twofold: Locate the part at the desired orientation, and to avoid distortions due to own weight or to clamping forces.

WP4: ADAPTRONIC MACHINE CONTROL SYSTEM

This work package aims to obtain a control system that will decide which of the gadgets has to be activated at each moment. It will be able to work in different machines, equipped with different numbers of gadget. Depending on the particular case, the strategy to be used by each one of the gadgets that will be activated will also be defined by this control system.

The software developed will run on different control hardware platforms. The idea is to be able to work at any open control system, so as for the project to obtain maximum impact.

The first task in this work package is the definition of the data exchange with each of the gadgets. The interface between control unit and the gadget is a software wrapper based on OPC XML-DA specifications. This module also provides the gadget with a standard interface to communicate with other components if necessary.

The Control Unit Engine is the core of the Control Unit. It is a rule based engine that implements the intelligence to activate every gadget when it is needed. This intelligence is implemented by rules that must be defined in the project. These rules are not static and can be customized to every machine and installation.

Because the control unit engine uses OPC XML-DA to read and write variables, we can add parameters from the CNC and other OPC XML-DA compliant devices to the rules to get a multivariable system. When a rule is true the engine can launch two types of actions:

- To write a value in an OPC XML-DA variable to control the action of a gadget, CNC or another device.
- To invoke other web service. This capacity can be used to fire other types of tasks as notifications, register, orchestration�

The control system developed will have also an important communication with the machine user. This communication has to be performed in a user-friendly way, in such a way that the machine�s extended performance is as transparent to the machine user as possible.

As a final goal, the task will provide a software system compatible with open control systems, able to work with machines incorporating different number of gadgets and using them in an intelligent way, in a user friendly context

Project Results:

WP1 Adaptronic head

T1.1 Extended Performance Magnetic Spindle

The objective of this task is the attainment of a working head able to machine in very different conditions. The head is based in magnetic levitating bearings, because of their adaptability to different situations. Magnetic bearings allow adapting the spindle in different ways:

- Stiffness of the spindle can be adapted. Although almost in all situations the maximum stiffness will be desired, the stiffness can be changed in order to reduce the forces transmitted to the machine. The stiffness of the spindle is defined by the control system, so during task T.1.1.3 will be developed this adaptability.
- The rotation axis can be selected. For example, instead of rotating in the geometrical axe defined by the position sensors (the standard working situation), the real inertial axis can be used to rotate. If inertial axis is used, vibration due to centrifugal forces and noise in general, is reduced. In this case, the difficulty resides in knowing which the inertial axis is. Balancing of the shaft will change the inertial axis of the shaft, so during T.1.1.1 the shaft is balanced to match inertial axis and the axe defined by the position sensors.
- The damping of the shaft can be regulated. Magnetic bearing spindles usually have a low damping value, due to the lack of energy loss in shaft (where the bearing forces are applied). To be able to increase the damping of in the shaft, a sensorless measuring capacity is needed, and afterwards this knowledge is applied in new control algorithms. So this, adaptability is developed during tasks T.1.1.2 and T.1.1.3.

T1.1.1 Three plane balancing

Due to manufacturing tolerances, every manufactured shaft will have a degree of unbalancing. Depending on the shape of the shaft, one or two balancing planes are habitually used. But, when rotating at high speeds, a third balancing plane is needed, in order to decrease the vibrations and the deformation of the shaft. In order to study the effect of the unbalancing forces when rotating at high speeds, a rotordynamic model for a magnetic bearing spindle has been developed. This model includes the behaviour of the shaft at high speed rotations (gyroscopic effects) and the influence of unbalance.

This model approach is based on Finite Element method and its elements are described as individual elements that could be modelled easily. This method could be done in a simple way, even with shafts with quite complex geometries.

Each element is not only modelled with inertia, mass, damping, and stiffness properties, but also they are modelled with the unbalance properties. This last property allows the test of three plane balancing method in a theoretical method. This method is safer than doing it with real system, and also it could show the validity of one method in less time than changing masses in real system.

This model could be also used for natural frequency damping control analysis. With a higher effort, that is going to be done in next months, this model will include magnetic-electric actuator in order to test sensorless techniques that could improve the damping issue.

Two balancing methodologies have been theoretically analyzed:

- Modal balancing. This method will allow us to balance the shaft as rigid in a first step, rotating the shaft at low speeds (a standard two plane balancing is made first). And later, once two plane balancing is made, the third plane is balanced introducing a combination of masses in the three planes that is theoretically balanced in two planes.
- Sensitivity coefficient approximation. A test mass is introduced in each plane, and after making tests at different speeds, the data is introduced in a model. The result of the model is the needed masses in each plane in order to balance the shaft.

Modal balancing has been used to make a rough balancing in three planes. Afterwards, the sensitivity coefficient approximation has been used to make a finer balancing. And finally, the theoretical model has been used to make the finest balancing.

Prior to 3 plane balancing the rotating speed of the shaft could not be over 20,000 rpm. After balancing has been made, the rotating speed can go close to the first natural frequency of the shaft, 34,500 rpm in the spindle of chameleon project.

T1.1.2. Sensorless measuring capacity

In order to be able to provide damping to the shaft, the standard measurement of the position is not enough. If the position could be measured exactly in the centre of the magnetic bearing, a feedback of the measured speed in the control would be enough to provide damping in the shafts natural frequency.

Different ways to get the sensor less measuring capacity have been detected:

- Electrical model of the actuator. Knowing the applied voltage and the resultant current, the inductance value of the bearing can be estimated. And the inductance and the rotor position are related, so by means of an observer, a estimation of the position in the centre of the bearing could be obtained.
- Mechanical model of the shaft. A mechanical observer, can filter the signals that are due to the natural frequency of the shaft. This filtered signal, after amplification and phase shift will be added to the feedback of the control.
- Injection of high frequency noise in the coils and measurement of the current response.

After rejecting the other two alternatives, the possibility to induce high frequency voltage in the coils and measure the corresponding current has been analysed. The dynamical behaviour of the current depending on the introduced voltage in a coil depends on the inductance of the coil. And, in a magnetic bearing spindle, the coil inductance is dependent on the position of the shaft in the middle of the magnetic bearing actuator. So, in a magnetic bearing actuator, if a sinusoidal voltage is induced, the induced sinusoidal current is dependent on the position of the shaft in the bearing. The implementation of this methodology in the magnetic bearing spindle, has needed some hardware change in the electric cabinet of the system. Originally, used power amplifiers in the coils where current controlled, so inducing a voltage is not possible with this configuration. So, in order to work in sensorless measuring capacity, 4 of the used 10 power amplifiers have been changed to in house made power amplifiers, where the current loop is closed in our electronics hardware, so we have all the control of the applied voltages.

Sensor-less measuring system implementation

For the measurement of the current, an electronic circuit has been developed with some filters and a hall effect current measurement sensor. The filtering system has been developed in a way that only the current corresponding to the introduced noise in the amplifiers is measured. This system has been implemented and tested during the project.

T1.1.3 Optimization of control strategy and parameters

In order to be able to operate with the maximum performance of the magnetic levitated spindle, the control strategy and parameters have to be tuned to the optimal condition. This tuning can be made, when the behaviour of the system is completely known. Due to manufacturing process of the spindle, the behaviour of the magnetic actuators is not completely known for different positions of the shaft.

A methodology to identify the exact properties of the actuators has been developed. The methodology has been implemented in the control system of the spindle. The identification is made automatically by means of a software that has been developed for this task. All the actuators of the system have already been identified. So the exact magnetic center of each actuator is now known. This information is being used to tune the overall control system of the spindle. After identifying the exact central point a small test bench has also been developed to identify the force that the spindle is able to make. This way, all the magnetic actuators parameter are known, and using this knowledge the control system has been improved.

3.1.2 T 1.2 Axis on Axis

Work focused in the analysis and development of the most suitable strategies (T1.2.1)

T1.2.1 Development of displacement sharing strategy

Different displacement sharing strategies for the machine drives and spindle axis have been analyzed, lineal and non lineal axis on axis has been developed. During the last task (T1.2.3), developed algorithms have been implemented in a milling machine with a Fagor 8070 control. Machining tests have been made during the last task.

Conventional axis on axis

The input to the system is divided into 2 signals. Two filters are used for that purpose. The first filter is a lowpass filter with a stopband frequency below the natural frequency of the low-siffness axis. The second filter is the complementary filter to the first one: a highpass filter with a passband frequency over the natural frequency of the low stiffness axis.

For a given trajectory the error improvement along the path can be in the order of 70% depending on the dynamic properties of the elements and the spectral composition of the trajectory itself.

Depending on the type filters used in the axis on axis system the accuracy reached on the goal trajectory will vary. Two types of filters have been tested. In the first one (method 1) a low pass filter with an abrupt decay is adjusted below the frequency of the position loop of the main axis. The results obtained are shown on table 1. The second method consists in defining a filter based on the transfer function representation of the main axis. The closer capture of the behavior of the main axis with this second method leads to an improvement of the error generated along the trajectory (see table 1).

In spite of the precision improvement, the main drawback of the previous model is that, unless the system�s behaviour is very precisely identified and described in filter form, it cannot be used when the axis length is very limited, as it is the case of the magnetic head. Amplitudes of about ± 3 mm are required in the high stiffness axis for optimal performance with common trajectories. However the displacement allowed by the magnetic head is in the order of ± 0,2 mm. In order to overcome this limitation a new axis on axis strategy is proposed in Fig 3. No filters are used in this case and the high stiffness axis gets the error feedback from the low stiffness axis and tends to correct it. The required amplitudes are in the order of the error made by the weak axis which can be kept well below 0,2 mm if the acceleration and jerk parameters in axis 1 are reasonably introduced.

A significant error improvement can be achieved in this configuration using a magnetic head as high stiffness axis (up to 80-90% depending on the dynamic properties of the elements and the spectral composition of the trajectory itself).

T1.2.2 Non linear control development

As the displacement of the magnetic head is limited the system will not be able to follow trajectories surpassing this limit. The effect of this displacement limitation can be simulated by introducing a saturation block on the control loop of the magnetic head. Several simulations have been performed in order to overcome the non-linearities introduced by this spatial saturation. However the new axis on axis technique proposed in which the error of the main axis is used as feedback for the magnetic head, allows to work on spatial regions far away from the limiting points and to get rid of all these difficulties.

A model has been developed where the measurement of the error between the commanded position and the real position of the main axis is transmitted to the secondary axis. This model has shown that the system works properly if this signal can be passed from the first axis to the second. During the test and improvement task, the standard model and the non linear model have been compared. Although the improvement of the non linear model was not big, the system was more reliable and more stable with the non linear model.

T1.2.3 Test and improvement

During the first months of this task, machining tests have been made in the magnetic bearing spindle. During the first tests a problem in the measurement of the eddy current sensors in the spindle was detected. In order to identify the problem source a test bench for the sensors with a magnetic actuator has been developed and manufactured. Tests made within the test-bench have defined a reengineering needed in the spindle, so a change has been made in the magnetic bearing spindle. This was a big problem for the project, but as it was detected quite early it has not affect in the overall result.

Two type of axis on axis system have been implemented: filter-based axis on axis and error-based axis on axis.

The machine in which the magnetic spindle has been mounted is equipped with a Fagor 8070 CNC controller. Filtering of the target trajectory can be made by defining a filter in 2 ways (note that for a machine axis the filter will be in general a low-pass filter). So the filter based axis on axis has two ways to be implemented:

- Using the machine HMI for the definition of the filter (on HMI.DIAGNOSIS.OPTION in the Fagor 8070 controller). This is the method that
- Defining the proper FIR filter coefficients separately in a txt file. The filter is defined by setting the number of coefficients in the first column and indicating the coefficients with double precision in the following columns. Then the file is placed on folder CNC8070/MTB/DATA folder in the Fagor 8070 controller.

The implementation of the error-based axis on axis does not require any filter to be introduced in the trajectory command path. In this case the following error of the machine axes must be commanded to the magnetic spindle. There are two implementation possibilities for such approach (although just the second one has been used):

- Via PLC: the following error of the machine axes is read in the PLC and is then commanded out analogically to the magnetic spindle.
- Via motor drive: the machine in which the magnetic spindle has been installed is equipped with Indramat DEAS 02 drives. Such encoders have encoder simulation outputs which, once configured according to the drive manual, provide the following error of the machine axes without the need of taking it from the CNC or PLC.

T.1.3 Ultrasonic vibration aided machining

A few changes regarding the DOW have been performed: Ultrasonic vibration becomes Sonic since patent owns by Sauer (DMG) in ultrasonic vibration (fixed frequency) prevents any work from being performed in that field. Therefore an innovating approach in drilling and milling operation consists in working at low frequency on a large range of speed.

The active component initially made of piezo becomes magnetostrictive: piezo actuator in rotation required slip rings to transfer the energy from the stationary frame to the rotating one. Alternatively complex design with bearings can be possible but limits the life time. Magnetostrictive component gets ride of this design constrain.

Elsewhere, a sonotrode coupled with magnetic bearing appears to be not compatible at low frequency. It required extra-large length sonotrode & low coupling. Therefore the integration of a sonotrode at the tip of the magnetic bearing becomes impossible.

Finally one demonstrator of piezo tool holder is delivered. At the subsystem level the actuator display 23µm of stroke and 12kN of force. In addition one prototype of magnetostrictive tool holder is delivered. At the subsystem level the actuator display 95µm of stroke and 8kN of force. These deliverable are shown below

Both demonstrator and prototype have been integrated and tested on a machine tool:

- The magnetostrictive prototype integrated on Soraluce machine tool at IDEKO
- The piezo demonstrator is integrated on CEDRAT dedicated bench at Cedrat.

Both systems required interface definitions to be controlled in sonic condition:

GENERAL CONCLUSIONS:

The process of vibration assistance is validated in drilling operation: in the following material:

- Wood, Steel, Aluminum, titanium and composite (carbon / titanium)

Low frequency and large stroke is required to validate the process. Then short stroke piezo tool Holder and ultrasonic generators are not suitable.

The vibration assistance help reducing the chip size leading to:

- Better quality: roughness reduced by a factor three
- Tool Life time increase: + 50% (129 holes drilled in abrasive material)
- Possibility to realize hole in composite material

Finally the Prototype of magnetostrictive tool holder is optimized and displays interesting performances:

- Vibration performances: 150µm / 9kN
- It increases the rigidity of the tool holder for Milling operation (no tested)

- It increases the productivity (large force) with greater feeding advance capability

WP2: ADAPTRONIC STRUCTURE

The mechanical structure of a machine tool is its basic component, and provides some of the key characteristics to its performance. Within Work Package 2 the project dealt with the integration of adaptable, mechatronic concepts into these, in many cases huge, mechanical structures (e.g. boring machines). The overall goal was to enable the machine tool to cope with different manufacturing requirements that normally contradict each other. For instance, when using a machine tool for different types of processes, e.g. heavy cutting and high-speed machining, low-weight design and high feed dynamics conflict with high stiffness requirements.

1.1.1 Configuration for High Requirement Conditions

Depending on the load that is introduced to the machine tool during the cutting process, the geometry of the machine tool changes due to static and dynamic deformations. The Active Error Compensation aims at compensating these displacements by the use of active, structure-integrated components which will, in consequence, ensure a higher accuracy of the machining results. Within this task, a system including an actuator and a controller for the compensation of static deviations had to be developed. The system was planned to aid with the adaption of a light-weight high speed machine to heavy roughing operations and to increase the multi-functionality of a standard machining centre to different heavy-duty operations. Due to the stand-alone compensation control electronics the system is able to adaptively change the control strategy as required by the different types of cutting processes. This enables the machine tool user to perform more operations on one workpiece on the same machine and thus reduce time for transport and setup of the workpieces.

1.1.2 Configuration for High Precision Mode

The global accuracy of large machining centres changes over time with the life-cycle of the machine, the force load and the temperature of the environment. For high-accuracy machines regular calibration strategies and temperature-controlled surroundings are necessary in order to ensure high accuracy over the complete workspace at all times. The required effort for calibration and temperature control is typically very high. Volumetric calibration of large machine tools is usually done manually using a laser interferometer causing non-productive times. Within this task, a calibration strategy had to be developed to allow for the rapid adjustment of volumetric compensation of thermal and static displacements during the operation of the machine tool. By the use of wireless transmitters, this strategy would be based on direct displacement measurement of the machine�s tool centre point (TCP). With the on-line rapid calibration system to be developed a standard large machine tool could, in theory, be fitted to produce high accuracy output.

1.1.3 Configuration for High Material Removal Rate

Machine tool manufacturers are aware of the limitations of their machines caused by the appearance of self-excited vibrations, known as chatter, during the machining process. Obtaining machines more resistant to chatter requires having higher rigidity and / or higher damping. As damping cannot be controlled in general more rigid machines has always been the trend, but this implies higher costs. Passive absorbers are only useful for a very narrow frequency range, thus being of limited interest for machines aiming to work in a wide range of parts and machining conditions. Active damping approaches are limited by the lack of suitable actuators and have not found a broad use yet. In this Task an active damping device had to be developed using a dynamic actuator based on the principle that accelerating a suspended mass results in a reaction force on the supporting structure. In this project it was intended to further develop this idea in order to deploy its full potential as a universal mechatronic device for chatter reduction being able to adapt to vibrations of very different frequencies.

1.1.4 Configuration for High Dynamics Mode

The dynamic behaviour of feed drives is usually improved using filter structures. The typical practice is to filter the reference signals that are generated by the NC. The most important benefit of the filtering is a higher useable bandwidth for feed drive systems. Otherwise, their natural limit would be the 1st resonance frequency. The most important disadvantage using this strategy in feed drives is that those filters can only be used outside the controller bandwidth. Therefore, the focus in this Task was to develop an adaptive control filter using the newest control and filter strategies to overcome the existing machines� dynamic limits. The filter structure to be developed had to be active, because otherwise it would decrease some performance parts of the signal. On the other hand the filter had to be an adaptive structure, since the varying masses of different workpieces would change the first resonance frequency.

Task 2.1: Active Error Compensation

After wide simulations in the first half period of the project, the existing test stand is put into operation. In order to reduce the masses the massive struts of the two compensation modules are replaced with hollow struts. The results of the test stand verify the simulation. With the structure integrated compensation the bending oscillation of the Z-Slider could be damped by a factor of approx. 10. The Figure 3 2 shows the dynamic compliance of the Z-Slider in X-direction without and with control.

Furthermore the picture shows the results measured with the massive and hollow struts. The resonance frequency of the struts (61 Hz) could be shifted to the higher frequencies. An improvement of the damping effect could not be achieved. Still the used piezoelectric actuators respectively the hybrid piezo-amplifier limit the damping result. The use of a hydraulic actuator with longer travel ranges may produce relief.

1.1.5 Hydraulic Actuator

Due to a use of machine intern energy cycles and the limited piezo travel ranges, a hydraulic actuator was developed for substitution of the piezoelectric actuators. Figure 3 3 shows the actuator sectional drawing of the actuator. The gliding gaskets are substituted by steel membranes for casing the pressure chambers and for guiding the piston. This avoids any flow of leak oil over the piston or the piston rod and improves, in consequence, the control quality and the dynamic behavior. The assembled actuator could reach a maximum travel range of approximately ± 300 µm.

1.1.6 Active Work piece Holder (AWH)

The productivity of machine tools is often limited by chatter vibrations which cause relative displacements between the tool and the work piece. In earlier research work, an active work piece holder with two high dynamic axes controlled by piezoelectric actuators was developed (see Figure 3 4). With these additional axes, the active work piece holder offers possibilities to prevent chattering at the TCP.

In order to improve the relative compliancy behavior at the TCP, tool side acceleration signals of the structure vibrations are captured. Based on the acceleration signals, the desired position of the work piece can be calculated to compensate the relative dynamic displacements at the TCP using the closed loop position controller of the associated axis of the AWH. In order to avoid relative displacement between spindle and work piece, the axis of the AWH moves the work piece following the spindle vibrations. The dominant machine resonance frequency causing process instabilities is hence made unobservable to the cutting process.

The damping effect of the assembled active work piece holder can be measured by comparing the dynamic compliance function with and without an activated control of the additional high dynamic axes. In Figure 3 5 the results of the optimized active work piece holder are demonstrated. The dynamic compliance is normed to the static stiffness. The frequency information is deleted as well in deference to the machine tool manufacture. A PI-controller is used for calculating the control signal.

Task 2.2: Rapid Calibration

A completely new concept of using interference pattern of spherical light waves as an absolute position measuring system was developed.

Figure 6 shows the simulation environment used for testing the algorithm. In a first step, different synthetic interference patterns were generated for a given starting position and different phase offsets between the point sources. This sequence of interference patterns along with a starting position, shifted by the amount of machine uncertainty, served as input for the algorithm which outputs a phase distribution and a calculated position in return. Both outputs were compared to their known counterparts and the difference between them (error of the algorithm) was plotted. Within the simulation environment it was possible to change several boundary conditions that have an influence on the stability and accuracy of the algorithm.

The basic setup for the test of the demonstrator system is depicted in Figure 7. The camera was attached to the movable table of the test stand which was developed and built during the project. It can move in two directions x and y. The demonstrator system (laser and optical components) was situated on the non-moving part of the test stand. A measurement cycle for the experiments was programmed by defining measurement points at which the camera would take several photos for different phase offsets between the two waves. These measurement points typically had the same distance to each other in y-direction for a given distance in x-direction and defined a test series. The different test series usually also had the same distance to each other which resulted in the exemplary measurement pattern seen in the picture. The entire measurement cycle was automated and handled by the test stand control unit. The photos taken were saved in a way which allowed for further automatic processing with the Rapid Calibration algorithm.

1.1.7 Significant Results

All preliminary tests were carried out using laboratory equipment in a controlled environment. To demonstrate the systems general ability to be used in an industrial environment, a demonstrator system was developed. The following aspects could be demonstrated using this device:

- Miniaturisation of the setup of the optical components
- Clear separation of laser and control electronics on the one side and optical components on the other side
- Robust housing of the optical components
- Possibility to fine-tune the optical axes of all optical components
- Reliable connection of laser and optical components

Picture 1: View of the demonstrator System

The following two diagrams (Figure 8 and Figure 9) show the results of a measurement cycle comparable to the one of Figure 7. In each diagram the difference between the measured position and the nominal position is plotted component-wise against the current position of the test stand for each test series. The test series are represented by different colours and markers. Missing markers mean that the measurement at this position failed for instance due to disturbances in the intensity pictures. The results for the x component are shown in the first diagram. The overall error for all measurement points lies in between a range of -0.5+1.3 mm. The error of the y component in the second diagram is significantly higher and lies in between a range of -4.5+3 mm. The starting position of the algorithm had an offset of about 40 mm which is still a magnitude higher than the resulting error.

1.1.8 Deviations from Planned Work and Objectives

Although the errors might seem a lot, one has to bear in mind that wavefront distortion has a huge effect on the accuracy of the Rapid Calibration algorithm. For the tests shown in the diagrams a system based on spherical lenses was used as the new lens holder was still in construction. This leads to the effects of optical aberration which of course impair system performance. In addition, simulations presented in deliverable 2.2.2 have already shown that a low colour depth of the CCD camera will limit the accuracy of the system. A colour depth of only 12 bit, for instance, which was the case for the measurements, will keep the error in a range of 10-4 to 10-3 m. Nonetheless, the presented results demonstrate the basic functionality of the algorithm and the hardware that were developed during the project.

The results show that the physical principle of the measurement setup works but the performance is still below the theoretical accuracy which was suggested by the simulation results. During the research and development activities of the project several issues were identified that have a critical impact on the behaviour of the entire system. Some of them could be solved completely within the project duration (like drift caused by optical fibres); however, some of them have yet to be sorted out:

- Limited colour depth of CCD camera
- Optical aberration due to spherical lenses
- Accuracy and repeatability of phase shifting device

Task 2.3: Active Damping

1.1.9 Initial state

Machine tool manufacturers are aware of the limitations of their machines caused by the appearance of self-excited vibrations, known as chatter, during the machining process. This has made chatter avoidance a matter of interest among specialists for a long time. Obtaining machines more resistant to chatter requires having higher rigidity and/or higher damping. As damping cannot be controlled in general more rigid machines has always been the trend, but this implies higher costs. Some devices to increase damping have been proposed, like the damping pads in the slide ways, but they only had limited success.

In some applications, added damping by using tuned dynamic absorbers has proved to be very successful. Nevertheless, these passive absorbers are only useful for a very narrow frequency range, thus being of limited interest for machines aiming to work in a wide range of parts and machining conditions.

Active damping approaches present a number of advantages compared to passive techniques, but unfortunately they are limited by the lack of suitable actuators and have not found a broad use yet.

1.1.10 Objectives

In the frame of the European Project SMARTOOL (FP5 GRD2-2000-30314), Micromega and Ideko have developed and successfully tested an active damping device using inertial actuators. This kind of dynamic actuator is based in the principle that accelerating a suspended mass results in a reaction force on the supporting structure, and behaves as a perfect force generator above its suspension frequency. In the Chameleon project it is intended to further develop this idea in order to deploy its full potential as a universal mechatronic device for chatter reduction.

Active inertial absorbers will advantageously replace passive absorbers, as they will be adaptable to vibration of very different frequencies. A control system that will identify the frequency range at which the active absorber must be effective will be developed. The communication with the controlling system for the complete intelligent adaptive machine will provide information helping the identification of the frequency range of interest.

1.1.11 Tasks performed

Based on the specifications coming from Ideko, the design of a bi-directional Active Damping Device (ADD) has been realized. This ADD experiences the following characteristics:

- Maximum Damping Force: 1400N (2 axis)
- Bandwidth (20Hz 500Hz)
- No preferential direction no sensitivity to gravity
- Flexible digital control unit
    - Structural Damping control algorithm insensitive to natural frequency changes
    - Implementation of Notch filter to prevent the control of the machine suspension
    - User friendly Man_Machine_Interface

Figure 10 shows the engineering model of the Chameleon ADD. The ADD is made of a 30kg moving mass suspended by rubber mounts at a suspension frequency of 22Hz, in order to limit the deflection due to the gravity). The actuator consists of Voice Coils Actuators (VCA), for which the Lorentz force is provided by an electrical current flowing in a magnetic field. This latter is generated by permanent magnets, whose flux are guided by ferromagnetic parts. In order to avoid moving electrical connection and to limit the actuator weight, the magnetic flux generation circuit are embedded in the actuator moving mass. Finally, the ADD acceleration sensors are mounted in the device in order to achieve force/sensor collocation.

The ADD has been successfully tested on the new FL-Milling machine from Soraluce. Next Figure shows the ADD implemented on the milling machine and the reduction of the dynamic amplification at the main machine resonance (32Hz).

ADD on machine and active damping results

Finally machining tests have been realized by Ideko. The objective is to check how much the stability margin can be increased with the inertial actuator. Different ram outputs are considered. The spindle speed is 550rpm and the feed per tooth is Fz = 0.1 mm/z. The tool has 8 inserts and its diameter is 125 mm, while the radial immersion is ae = 100 mm. shows a typical tests results were a 50% increase of the cutting depth, hence the productivity, has been observed.

No deviations from the DOW have occurred during the frame of the CHAMELEON project. All the objectives described here above have been met.

3.6 Task 2.4: Active Filtering

The goal of this task is to increase the dynamically usable range of feed drives by using an active filter structure. In order to achieve this, the eigenfrequencies have to be damped. In the approach of this project, the active filter structure (AFS) is placed in the feedback path of the position measurement system and thus manipulates the measurement signal before returning it to the controller. The measurement signal is filtered by a band-stop. The principle of the AFS is shown in Figure 11.

Figure 11: Principle of the AFS

Measurements on a project demonstrator have shown that machine tools typically have a different resonance behavior at different axes positions. As can be seen on the example in ¡Error! No se encuentra el origen de la referencia., the resonance frequency does not change significantly (?<1.6 Hz) in that case, but the amplitude overshoot differs from the minimum to the maximum of about ?=13 dB.

To always get a good filter result, it is necessary to adapt the filter to its according overshoots and resonance frequencies. Therefore, a position dependent structure was introduced as shown in next Figure. With this structure, it is possible to generate new filter parameters within the sampling rate of the position control loop. But since the calculation of new filter parameters is not feasible for real time applications, a number of possible filter parameters are pre-calculated and then selected out of memory during runtime. This yields in an efficient way of adapting the filter function for different positions.

The results of the different filters for different positions are shown in ¡Error! No se encuentra el origen de la referencia.. It can be observed that the AFS is indeed able to adapt itself to the current overshoot of the machine and therefore is able to damp the overshoot at 19 Hz to a constant level for different positions.

WP3. ADAPTRONIC WORKHOLDING

T3.1 Raw part location

Characterisation of the raw part was decided to be done by means of photogrammetry. The method consists in applying coded and uncoded retroreflectant targets at the surfaces to be machined, and taking photographs from several positions.

Photogrammetry will provide the 3D coordinates of the targets, therefore the raw surfaces are characterised. Then, two further steps are required:

- Comparison with the designed final part
- Location of part in machine

It was found that photogrammetry has an important problem of robustness when dealing with parts that have surfaces to be characterised in very different planes. The problem comes from the analysis system being unable to understand the codification of the coded targets. To fix this issue, multicoded targets were developed. As a result, photogrammetry is now very robust. Multicoded targets are shown in the following picture:

Comparison of raw part with the designed final part requires acquiring the CAD design of the part, what seems quite complicated to be done for different CAD systems. Therefore, acquiring the geometry of the final part from the machining CNC program was decided. This acquisition was automated for the flat surfaces, and was also developed for cylindrical shapes. A comparison algorithm that allows determining the appropriate raw part reference axes was developed.

Once the raw part reference axes are known, the next step would be to locate the part into the machine with its axes referenced with regard to those of the machine. For that, the decision taken was to use stereo-photogrammetry. To use this technique, a single camera will be located on a tool holder and mounted on the spindle head. The head will approach consecutively three or four targets of the part, and by taking some photographs (minimum of two photographs), the location of the target in machine coordinates will be known.

Comparing machine coordinates of the targets with the coordinates of the targets in raw part coordinates will provide the required rotations to be given to the part, and the translations to be given to the machine axes.

The procedure was tested and provided good accuracy. A specially devoted hardware integrating a camera on a standard toolholder was developed. Next picture shows the toolholder and the images taken of a coded target from two different position of the machine axes.

A representative part, having interchangeable surfaces to machine, was designed by a collaborative work by SEEB and Ideko. The part is being built by SEEB, and because of the interchangeable surfaces, complete testing can be done several times.

Task 3.2 Fiducials locating system.

The solution adopted consists of a vision system linked to the main spindle of the machine. Controlled orientation of the spindle provides different, known, vision points of the fiducial (sphere of circle). In this way, two or more images obtained from different orientations of the spindle provide the information to calculate the position of the fiducial.

Next figure shows the tool designed and fabricated to hold the camera and the lighting system. The system is clamped into the spindle taper, and is oriented by the controlled rotation of it. In that way, image for different camera locations can be obtained, and the coordinates of the fiducial can be calculated. Also in the same figure it is shown how the software developed obtains the real orientation of the camera. The previous calibration software process makes possible to achieve and calculate the camera coordinates for each image.

The software for calculating the coordinates of the fiducial (retroreflectant sphere) was developed as well as the calibration for the extrinsic parameters of the camera. The system was optimised and incertitude of location of the fiducial was reduced to about 1 ?m. Incertitude analysis is difficult, as the measurements are based on the positioning of the machine, which has an incertitude worse than that of the system developed.

Current measurement procedure is quite slow, as it requires about one minute to measure the position of one fiducial. Ways to reduce this time are being considered.

Task 3.3. Adaptronic Workholding

Large parts are difficult to be manipulated, so as to locate them in the correct machine position. Besides, application of clamping forces in a manual, uncontrolled way, gives rise to part deformation. After unclamping, the distortion of the part disappears, but then the accuracy of the machining operations performed by the machine will be lost.

The goal here was to develop intelligent fixtures, which can apply small displacements to the part so as to locate it in its proper position with respect to the machine, and to measure the forces applied, to avoid distortion of the part.

Modular fixtures were developed. That includes the design, prototyping, and testing. Four prototypes were built, and tested with an scale model of a railway bogie.

Testing included displacement capacity, displacement measurement accuracy, force capacity and measurement accuracy, and clamping force.

WP4: ADAPTRONIC MACHINE CONTROL SYSTEM

An adaptive machine will be able to work in different ways. It will be more and more complicate to the shop operator to control all the different devices / gadgets of the machine, and select their best possible parameters, including activation or deactivation.

For this reason, an intelligent control system is needed. The development in project Chameleon includes an standard for communication of the gadgets with the intelligent control, as well as an expert system that will learn from experience and will communicate and assist the operator in tuning the machine for the operations to be performed.

The decision system is based on rules. A rule may have a cost (in time and/or money) associated to its antecedent, as well as a degree of importance and a feasibility threshold.

Analysis and Data pre-processing: During the usage of the machine, gadgets will store information massively. Use of machine learning techniques requires carrying out a deep analysis and data pre-processing before selecting the algorithms that will be used.

Process data: Data related to the definition of the machining process, machine data and gadgets data. This data is enriched with statistical information about it and presented to the machine learning system. More information was added related with time series.

Selection of algorithms and integration of expert system: In this task, once pre-processed data was obtained, a selection of the different algorithms that best suit to the case study was carried out. This involves testing algorithms in the first place. Then, as a final result, the most suitable algorithm for improving the expert system was selected.

Control Unit Based on Rules

The Control Unit is the module in charge of analyzing some conditions and act according to some procedures described in the configuration of that module.

The Control Unit is based on web services. This ensures the interoperability of this module with others existing in the project, connectivity services, variables registering services, access to actuators and will offer the possibility for this module to use other web services in the future.

The data of analog and/or digital signals is acquired through web services. The OPC XML-DA standard is widely used in the industry and is based on web services. Thus, the Control Unit is an OPC XML-DA client of these servers.

Architecture

The main functionality of the Control Unit is the coordination of the gadgets of the system; i.e. it is in charge of analyzing the set conditions and carrying out the programmed actions.

The central element of the system is the rule engine. This module is in charge of loading data and manage the interaction logic between the Control Unit and the outside world.

The file of rules definition is read and analyzed for loading data and rules. This analysis is carried out by the parser together with the creation of data structures optimized so, later on, the evaluator evaluates the rules and the OPC XML-DA client reads the values of the external variables.

The OPC XML-DA client is in charge of reading and writing the values of the external variables. This client must implement the logic and formats indicated by that specification. For optimizing the communication with the OPC XML-DA server and the rule evaluator, a cache mechanism is been implemented similar to the one implemented by the OPC XML-DA specification itself. The OPC XML DA client reads the value of the variable and assigns it to the corresponding variable of the cache.

Monitoring Service Interface

The Control Unit is a module with very little direct interactivity with the user. Interactivity is provided by the rest of the services that are executed by configuration of the rules.

The functionalities offered as server are to start and stop the component on one hand and to obtain or load the rules that dictate the operation of the module on the other.

These web service methods allow that rules will change dynamically when results of task 4.3 will be applied.

Rule Editor

The rule definition can be a very hard task to people that is not familiar with typical IF-THEN-ELSE rule structure. This type of rules are easy to understand and define to people working on programming task but can be difficult for people involved in machine operation.

The most simple and effective approach to define this type of rules is the decision tables. In order to facilitate the user operation a custom control table template has been developed. This template offers a simple structure to fill the IF part and the corresponding THEN and/or ELSE part.

The condition part can have a maximum of four terms and three operators. Generally this is enough to almost all rules but if it is needed to evaluate more terms is possible to use local variables to discompose one complicated condition into a several simple conditions.

The template is a Microsoft Excel 2003 template. In order to offer a tabular format with helps to the user like list of selectable values, a spreadsheet is the most wide usage application type.

The user can generate a new rule set or edit an existing one with some of the tools previously mentioned and save the rules in a file.

The application allows stop, load a new rule set and start again the Control Unit to give the user the capacities of changing the rules applied by the Control Unit.

Chameleon machine

At the Chameleon machine, the intelligent devices and their correspondent gadgets work supervised by the control unit under a set of rules that is not fixed but that may grow through the input of the experts, using the rule editor, or automatically, through the output from the experience based decision support system. This output is based in the analysis done on the acquired data from the different gadgets and the machine itself during the life of the machine.

A first basic rules set is shown, as the initial set of rules that had been implemented in the prototype developed under Chameleon project, and that represents the start point.

The rules are ordered attending to the intelligent device and to operation state of the machine, whether it is in setup or in process.

Experience based decision support system

One of the goals of the project is to make the control system be able to learn from experience, in a way that its performance is improved. In the previous task it was implemented a production rule system that fires rules when their preconditions are met. But the rules are static and no are subject to changes during the working of the system. In this task the main goal is to gather information from the working system and, using machine learning techniques, to be able to come with better rules than the initial ones. To this end first a definition of the experiments to be made is needed in order to get the most useful information about the correct working of the system. The data coming from the gadgets will be preprocessed to be fed into the machine learning algorithms that will give as an output a better version of the rules currently applied.

Potential Impact:

The Machine Tool Industry is a key sector because of its strategic importance for the rest of industries, with a direct employment in Europe of about 200,000 people. The business conditions lead the companies to a further and non-stop development of faster, more flexible and intelligent machines that are also more productive and accurate.

The development of chameleon-like high-end multifunctional machines will allow European builders to stay ahead of the competition in the global economy. This will allow conquering a larger share of the market and, as a consequence, increasing the turnover and the direct and indirect employment in European countries.

In 2005, the machine tool production in the CECIMO countries amounted to 18.111M�, which represents an increase of 9.1% compared with the previous year. However, in the last years, the machine tool production share of the European Union has decreased significantly. In 2002, the machine tool production share by the CECIMO countries represented the 52.4% of the overall world production, whereas in 2005, this share dropped to 44.3%

The strong burst onto the world machine tool scene by countries like Taiwan or South Korea is increasing the world scale competitiveness and as a result, the European tool machine producers are losing market share in the last years.

In this world context, the development of new concept self-adaptive tool machines with high technology mechatronic devices implemented on it is a crucial point in order to stay ahead of the competition and recover and maintain the 50-55% share of the world market.

The ideas and concepts handled in this project would certainly bring out a number of benefits:

Replace the functionality of multiple specific purpose machine tools by a single multifunctional machine tool at a better cost.

New generation of advanced hi-tech components and instruments: magnetic bearings, universal active damping devices, intelligent workholding devices, fast calibration methods, active structures, fast reference processes�

New generation of high-end machine tools with an increased range of machinable parts

Optimal integration of machine tools and working accessories by means of advanced knowledge based software, allowing an always state-of-the-art machining operation

Reduction of the reconfiguration and maintenance time needed, as a result of the provided flexibility and adaptability of the self-adaptive machine.

Increased quality in big parts, so that production of high added value unitary or reduced batch parts will be done right first time

Reduction in the consumption of energy, due to the global machining time saving in high added value unitary or small batch part as a result of: fewer part moves (multiple operations, fiducials locating system�), reduced set-up time, optimum machine operation, less wasted time�

Decrease of the amount of raw materials needed for both the machine tool production (one machine for any operation) and the component production (assembly operations eliminated, do it right first time?).

Extended Performance Magnetic Spindle and Axis on Axis technology.

The problems found by conventional ball bearing spindles can be summarised as

- High maintenance costs.
- Typical period between maintenance operations: around 8000 hours.
- 90% of maintenance operations are to change bearings.
- Typical cost of a bearing change operation: around 7000 ?.
- Typical delivery time of a maintenance operation: around 3 weeks.

Therefore, a technical solution that reduce maintenance requirements would be appreciated by users of spindles.

The development done in Chameleon will make it possible to construct reliable magnetic bearing spindles, without the limitations found by this technology so far. Particularly, higher speed will be reached by three plane balancing, and higher cutting rate will be achieved by the sensorless measuring system. As a further achievement, reduction of heating and power consumption by the bearings up to 85% was obtained.

Axis on axis will be an inherently available technology at the magnetic bearings. The advantage of using this technology is the reduction of machining time in contouring operations, or the increase in accuracy if time is maintained.

The exploitation of the technology will be done by Goialde High Speed, Tekniker, and Fagor.

Goialde will be responsible for commercialisation, construction of mechanic components and bearings, and assembly. Tekniker will be responsible for manufacturing of sensors and of the hardware for the control of the bearings. Fagor will be responsible for the Software of Axis on Axis. Fagor will offer axis on axis as an independent solution also.

Target market sectors

- The sectors in which the new product developed in CHAMELEON project may have chances are industries that use intensively high speed manufacturing processes. We think the first sector to address could be the aerospace machining.
- This sector has strong growth prospects (EADS ?Conference may 2011?)

Ultrasonic Vibration Aided Machining

In drilling, cutting, turning or milling machines, the frequently occurred problems of chip formation and chip removal, burr formation at the cutter exit, tool stress, as well as process reliability and quality would be enhanced by these hybrid processes of overlapped energies.

Therefore significant improvement in part quality, tool lifetime and productivity would be performed.

The Ultrasonic vibration aided machining system developed results in a light and compact OEM sub-system with a high potential of integration.

After testing done, the results obtained are:

- Better quality: roughness reduce by 300%
- Tool Life time increase: + 50% (129 holes drilled in abrasive material)
- Possibility to realize hole in composite materials

The product price range will be between 10 and 20 k€, and the expected sales will be of 100 k€/year during the first 5 years.

Raw-part Inspection and fiducials locating system

Use of the raw-part inspection system will make possible to avoid the work of raw-part measuring and positioning at the machine. Nowadays, the typical time for this process is 16 hours, with an important risk of errors. The result is that in some of the surfaces to be machined more material is removed than could have been necessary, with a large risk of spoiling the part.

It is expected that raw-part inspection system combined with the intelligent workholding system will reduce the time required for positioning and clamping large raw-parts to less than 2 hours, with the added advantage of reducing the amount of material to be milled and with a large safety against spoiling the part.

Foreseen expected sell price will be 5000€ plus the costs of hardware and required labour for formation. It is expected that after 2013, more than 20 applications can be sold per year.

Fiducials Locating System

The use of fiducials provides a reliable reference making possible to ensure high accuracy in local areas of the workspace of the machine. This way, the long-range accuracy of large-scale machine tools will be improved.

Moreover, fiducials could be a very valuable resort in order to solve positioning errors produced when relocating the workpiece on the machine for additional machining operations. With the fiducials as a reference, there is no need to align and square the workpiece, which in consequence will reduce the required adjustment and set-up time. This will result in an increase of the availability of the machine.

Foreseen expected sell margin will be 4000€, and further formation activity will also produce some benefit. It is expected that after 2013, more than 20 applications can be sold per year.

Intelligent Fixtures

The use of intelligent workholding systems will bring along the following improvements for the manufacturing process:

- Significant reduction of changeover times between production steps resulting in an increase in available machining time. The changeover time can be reduced by 30%.
- Significant reduction of retooling times for new manufacturing tasks or workpieces through geometric adaptability of the clamping device
- Enhancement of machining accuracy and quality through a balanced share of clamping forces, thus avoiding wrapping of flexible workpieces. The static clamping errors may be reduced by 30%.

Possible customers are machine tool builders, who would incorporate the fixtures in their manufacturing system solutions, and also manufacturers of large parts (railway industry, wind and electric power manufacturing, car manufacturers and suppliers, etc.)

Exploitation of the development in Chameleon will require further measures :

- design of a model range of clamping modules with smaller and larger dimensions
- design of a type for aligning workpieces in a higher accuracy (0,02mm)
- integration of a more sensible force sensor system

The estimated further costs for exploitation are 50 k?

With regards to the competitors, only customer-specific designed gadgets are known. It is expected to have a lead over the competitors of 1-2 years.

The estimated market share is 1000 k?, with an estimated price per system of 120 k?. That means that the turnover increase for the company Dr. Matzat is around 50%

Active Error Compensation

The integration of the compensation control into the controller system of the machine tool will allow the adaptive change of control strategies as required by the different types of cutting processes. This enables the machine tool user to perform more operations on one workpiece on the same machine and thus reduce time for transport and setup of the workpieces. The angular accuracy in finishing operations can be reduced by up to 100 % depending on the method of error assessment. This facilitates the use of flank milling processes instead of point milling when manufacturing pockets or bores increasing the productivity by factors up to 10.

- The Active Work Piece Holder needs further research before exploitation is possible
- Research and development will be continued and funded by WZL
    - Development of an industry suitable solution of the AWH
    - Development of an industry suitable controller hardware
- Potential transfer project with industrial partners is an option if research goals are successfully met

- The Structure Integrated Compensation Modules need further research before exploitation is possible
    - Principle was successfully demonstrated on a test stand
    - Integration into a real machine tool as the next logical step
    - Hydraulic Actuators need to be optimised
- Application for further research funding is planned: Integration of structure integrated compensation modules into a portal milling machine (transfer project funded by DFG)

Rapid Calibration

The rapid calibration system to be developed, when fully integrated into the controller environment, will have a major impact on the ability to machine large workpieces with enhanced accuracy at reasonable costs. Today, high-accuracy machining of large workpieces involves multi-layered covers and housings for the complete machining centre, temperature control within less than 1 K, regular thermal and mechanical readjustment and regular laser calibration which may require e.g. 5 days of measurement each year.

With the on-line rapid calibration system to be developed, a standard large machine tool can be fitted to produce high accuracy output by actively measuring the TCP and compensating for temperature related changes. The expected costs of such a machining centre are 30 - 50 % of a high accuracy machining centre with the same workspace. The required floor space will be about 50 - 70 % due to smaller machine covers when temperature control is not needed. Typical SME machine tool users will be able to diversify to larger and more accurate products.

- The Rapid Calibration System needs further research before exploitation is possible
    - New geometric approach to accuracy measurement
    - Accuracy of current system needs to be improved
    - Robustness under real environmental conditions needs to be examined
- Research and development will be continued and funded by WZL
    - Principal elimination of current problems
    - Development of a fully working prototype system
- Potential transfer project with industrial partners is an option if research goals are successfully met
- Patent for the Rapid Calibration System handed in: 102011011286.3

Active Damping

Active damping will improve the machine tool performance by reducing the vibrations generated during the cutting process, both the forced vibrations and the chatter vibrations.

The active inertial absorbers will damp the vibrations of the tool head by means of their inertial actuators, increasing the dynamic rigidity of the system.

The wide frequency range covered by the damper will make the system adaptable to any kind of machining and the feedback gain and the control algorithm of the absorber will be conveniently tuned in order to face each specific situation. This possibility of tuning the active damping module will provide the machine tool with a high potential of flexibility and adaptability.

The approximate price for each application will be 20 k□, and the market size is estimated to be 500 k□ per year.

Active Filtering

The integration of active adaptive filter structures will allow the use of higher bandwidth control of the feed drives. The filter characteristics are adaptively changed with the setup of the machine tool and the drives first eigenfrequency.

With an active filtering system (AFS), an estimated improvement in the dynamic behaviour of feed drives of 40% could be achieved and the costs of a work piece decrease by more than 10%.

Active filtering developed in Chameleon project will be incorporated in all the machines by Doerries Scharmann, as an standard feature. The company thinks of this system as an important differentiation against competition, but there will be no direct economic impact. The benefit will come from the better quality of the machines, the reduction in manufacturing times, and enhanced precision, which should finalise by an improvement in the brand image and in an increase in sells.

Control System

Once all the intelligent devices developed in this project are implemented, co-ordinated and managed by the knowledge based software, the machine tool end user will have available a state-of-the-art control system. This control system will make possible to integrate into machine tools intelligent accessories and mechanisms that may be reconfigured dynamically, adapting a standard machine tool according to the machining process. In consequence, an adaptronic machine tool with expanded capabilities will be obtained.

Economical and social impact for end users

End users of cutting machine tool systems is a conglomerate of industrial sectors. This could be by large the industrial sector that would bring the largest economical impact of a successful completion of the project. Machine tools are used for production purposes where metal cutting could represent 10% of their turnover. Many of these industries are SMEs, so that the use of chameleon-like rapidly configurable machines would present a number of benefits for them:

- Lower investment in productive equipment
- Reduced machine set-up and production time
- Increased flexibility allowing tackling complementary production orders, especially for the production of single parts or reducing batches

- Produce parts right first time, with especial impact in the production of single parts or small batches

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