Executive summary:

The ADACOM project is a European collaborative project of the 7th Framework Programme. The aim of the project is to develop a generic modular adaptive control platform that will allow metal cutting processes to respond to changing circumstances by combining technologically advanced sensor systems, process adaptation strategies and actuator systems.

Presentation of the project and the consortium

The ADACOM project is a European collaborative project of the 7th Framework Programme within Theme 4, Nanosciences, Nanotechnologies, Materials and New Production Technologies. It is a four year project that started on October 2008 and will last until October 2012. A consortium of 12 partners coming from different fields of the technological world works on the project: 4 world leading OEMs (DAIMLER, FIAT, Heidelberg Druckmaschinen and BOSCH), 4 SMEs (LOLA, DIAD, ACTARUS, TEKS), the world leading sensor manufacturer (KISTLER) and 3 outstanding higher education centres (WZL-RWTH Aachen, Trinity College Dublin and Mondragon University) from 7 European countries.

The industries working on the project cover a broad range of sectors: automotive, industrial technologies, printing machine manufacture and aerospace applications. They have defined common daily production problems and together with the other partners of the consortium will work on the development of robust solutions. The proposed adaptive control platform will not only directly benefit the project partner industries but also will have a significant impact in industries involved in metal cutting and therefore will offer benefits for wider European industry.

Project Context and Objectives:

Background and context
The ADACOM project aimed to develop a generic modular adaptive control platform that will allow metal cutting processes to respond to changing circumstances by combining technologically advanced sensor systems, process adaptive control strategies and actuator systems. The consortium was a unique collaboration of some of Europe's leading industries as well as RTD performers in the field of process monitoring and control. One of the unique aspects of ADACOM is the industrial focus whereby a broad range of industry sectors including Automotive (DC, LOLA, CRF); Industrial technologies (BOSCH); Printing machine manufacturer (HDM) have defined common challenges which ADACOM targeted.

From a technological perspective the project set out to target the following goals:
1) The development of Adaptive Machining Systems for difficult metal cutting operations such as milling, turning, gun-drilling, and grinding, which consist of sensor and actuator systems for online manufacturing control related to the part quality. The major aim is to achieve an Online Quality Control system to satisfy demands for mass customisation and small batch production of gear wheel prototypes or drop-forge dies of Daimler and for the Heidelberger Druckmaschinen – applications of the above mentioned industrial sectors. In ADACOM, this aim has been achieved by separating the single components of an adaptive machining system into a modularised system. This modularisation approach promotes adaptation within the different modules to enable flexible use of the adaptive system for different machining operations in different end user sectors.

2) The next goal is the realisation of one central system for different processes, which incorporates the flexibility towards changing production situations, different machine tools and different work piece materials. This flexibility of the ADACOM-System has been reached by developing a standardisation of the Adaptive System components. Issues such as standardised interfaces, which guarantee "Plug and Produce"-production, have been addressed by standard data formats throughout the whole production sequence. This implies a connection of manufacture to design and enables the use of the same data in the design, production and quality assurance of a product to enable continued, uninterrupted production to meet demands in mass as well as small batch environmentally friendly and competitive productions. In the new manufacturing paradigm the emphasis is on manufacturing low numbers of high value components. In the aerospace and automotive sectors product differentiation is achieved through the manufacture of customised, cheaper, lighter, greener products. This is leading to the need to machining lighter, flexible, complex, components manufactured from innovative materials including titanium alloys, composites and metal-composite materials. By developing the appropriate software tools for intelligent process signal analysis, signal interpretation, life cycle data and systems to connect the data to the product, enormous economical, technological and scientific benefit to the European industry will be achieved.

New advanced materials have become attractive to designers, but the same material properties that have promoted their use have also been the source of various problems, specifically those which make them difficult to machine. ADACOM focused on certain priority material groups over all involved OEM sectors: heat-treated steel; high strength steel; aluminium alloys; cast irons and carbon fibre.

Objectives

The specific Science and Technology (S&T) objectives of the ADACOM project are:

- To increase tool life by 50%
- To reduce waste such as swarf and coolants by 80% and power consumption by 50%
- To reduce machining noise to less than70dBA
- To increase machining speeds for hardened steels and aluminium
- To increase throughput by 50%
- To reduce automatic and manual finishing operations by 80%
- To reduce lead times by 20%
- To ensure best-practice cutting methodologies for new materials based on a developed intelligent adaptive system which ensures the maximum performance of machining processes
- To develop adaptive and knowledge based integrated systems for high volume as well as small batch machining operations
- To ensure stable and part quality oriented production within the automotive, electronic and printing industry.

The high level objectives can only be achieved through the use of a collaborative research programme aimed to produce simultaneous advances in cutting and adaptive control system design. ADACOM promotes sustainable development by prolonging tool life, reducing waste and saving energy. For example, the costs of manufactured power train components for printing machines will be reduced by increasing machining speeds and at the same time ensuring a high level of process stability and part quality. Likewise, the cost of printing machine components such as printing cylinders will be reduced by lower reject cost due to increased process stability, part quality and machine availability. Tool life will be extended and machining speeds increased by using adaptive control systems and machining configurations which will make systems more fault tolerant. Fault detection will also be increased through condition monitoring so that dangerous malfunctions will be detected and machines will become 'production-safer'. Furthermore, due to the developments within ADACOM, new self-adaptive systems with online self-optimisation mechatronic concepts will ensure a high level of process stability and part quality. New machining strategies will allow right-first-time cutting to be performed, reducing both mechanical and manual finishing operations, thereby cutting costs and cycle times. The development of machine monitoring, communication strategies and ways to collect, distribute and use the data, will encourage better knowledge management. Advances such as these make European industry more competitive and able to compete in the world marketplace.

ADACOM's approach in addressing the call is shown below:

- ADACOM has developed the solution using the plug-and-produce approach
- Adaptive machining will lead to improved part quality, right first time machining, faster and greener machining and hence shorter development and cycle times. All of these factors will add to European competitiveness though the use of the ADACOM platform
- Predictive maintenance and system modularity will allow maintenance to be conducted only when it is needed and thereby reduce the time taken to carry this out.
- Right-first-time machining will make small batches more cost effective. System modularity will reduce change-over time between parts
- Better process control will lead to a significant reduction in rejects and an increase in tool-life. Both of these will reduce resource

consumption. It is expected that adaptive control of machines will also reduce power consumption and the amount of coolant needed. The basis for these reductions can be established through the ADACOM system, and the optimization can be realised and controlled on the ADACOM platform.

Overview of ADACOM approach

Due to the experience of the partners and good collaboration within the consortium in defining the scope even at the proposal stage, it was already specified that the adaption mechanisms would be based on four main approaches as shown in the figure below and the interaction demonstrates that the solutions are not mutually exclusive.

- Strategy Adaptation
- Position Adaptation
- Parameter Adaptation
- Machine State Adaptation

The standardisation and modularisation aspects addressed in WP2 set this work apart from the state of the art. Sensors in the machine tool collect information on the process, e.g. the temperature of the air, coolant, spindle motor, the pressure of the coolant. The new sensor solutions such as integrated vibration sensors, power measured on the NC and integrated tool temperature developed within ADACOM in WP3 also provide input to the adaptive control system. This dataset can be processed and correlated with machine state and work piece condition. Sophisticated knowledge based signal processing algorithms, data mining techniques and decision making algorithms have been developed and integrated into the core of the adaptive control system in WP 4. Adaptive control modes such as the concept shown above have been further defined and the disturbance can be compensated through adjustment within the modes.

From the perspective of the industry end users it was necessary to give significant consideration towards the development of a standardized approach to defining system boundaries as well as defining system architecture, input, constraints and outputs. This task was addressed in particular in WP 2 within the project. In advance of the development of sophisticated decision making algorithms to select the appropriate adaptive control mode or combination of modes, a standardized system definition was required. It has to be considered, that there are different types of sensor and signals, e.g. low frequency signal with slow changes such as a temperature change of the surrounding air and high frequency signals, e.g. cutting force and vibration as examined in WP3. The modularisation and reconfigurable aspects of the adaptive control concept will manage these input variations. The system's core should be universal to integrate in machine tool numeric controllers addressed in WP2, so that the software developed in WP4 is usable for many processes. The high level standardized system concept is shown in the figure below were inputs, constraints and outputs can be clearly seen in respective categories.

From this high level concept it was necessary to further define generic adaptive strategies appropriate for the various challenges identified by the industrial end users. The adaptive strategies were based on two main categories of online and offline adaption and this work formed the basis for the main scientific and technical development undertaken in the ADACOM project. The adaptive strategies defined in ADACOM also have the potential to become the single point of reference for adaptive control of machining processes as this approach combining the industry needs with the guidelines of standardization, modulatisation and reconfigurability have not been addressed up to now.

Tangible results from the demonstrated use of the ADACOM concept in the industrial partner sites with the project include:
- Increased tool life because of the stable conditions provided by the adaptive system. During the whole process the tool has a stable environment
- Online information of machine tools condition (e.g. state of the spindle, axis) and the possibility of preventative maintenance
- Decreasing tolerances of the work piece because of the better accuracy in the whole system
- Reduction/avoidance of ramp up work pieces
- Possibility to increase process parameters improvind throughput
- Avoidance of tool breaks
- Automatically identifying and stabilising critical parameter of the machine tool
- Reduced energy input to process, e.g. finding optimal energy input early in process
- Reduced waste parts by getting first part right
- Productivity improvement, optimal part throughput
- Reduced operator workload by using machine intelligence

Project Results:

1 Introduction

As the project is called ADACOM - Adaptive Control for Metal Cutting - the structure of the S & T report is based on the development of adaptive control strategies

In the first part, several adaption strategies that were identified within the project duration are presented in a clustered manner and their differences, advantages and restrictions are explained. The adaption strategies and their functionality describe the " Adaptive machining System". The functional units as identification, decision, and modification parts of the different strategies are highlighted. On this, the required hardware (WP2,3) and software (WP4) for adaptive control are presented. The hardware is divided to the control and data processing units (WP2) and the sensor and actuator systems (WP3). The software developments (WP4) are described in a clustered way of development emphasis. At the end of the report detailed information about the industrial case studies are presented that were implemented within ADACOM for the development, evaluation and demonstration of the different kinds of adaption. The industrial case studies were selected by the industrial end users of the project and are machining challenges from their productions. At the end of the project, all case studies resulted in a machining demonstrator that also was used for LCA, eco-profile and energy consumption evaluations of the different kind of machining systems. The result of the LCA, environmental and social aspects are presented in a special part of the final report.

2 Adaption System and Strategies

The inputs and outputs are differentiated to low dynamics and high dynamics. With regards to the outputs, the kind adaption is categorized: position, parameter, machine state or strategy adaption. Of course, the kinds of adaption can be combined to a more complex adaption system.

For the implementation of adaptive systems, in ADACOM different control strategies were identified, which possibility of use depends on the requirements and boundary conditions of the metal cutting process.

The strategies can be organized in two main groups:
- continuous closed loops
- iterative closed loops

In the following section these groups with their sub modes are described.

2.1 Adaptive control strategies with continuous closed loop control

The continuous closed loop control attempts to in real time automatically maintain the control variable at a specific set point based on information from the measurement system by manipulating the actuating variable through the controller. In this control strategy three different modes have been identified:
- Static control parameters
- Parameter adaption with continuous plant identification
- Parameter and process model adaption

In the control strategies, two loops are employed:
- The inner loop or feedback loop: provides information about the process state. This loop is essential for the control task and therefore is present in all strategies, it would be however be modified for processes where iteration are necessary as will be explained in the next section.

- The outer loop or adaption loop: provides the feedback for the controller parameters. This loop is used in the continuous adaptive control strategies with continuous plant identification and process model adaption.

The simplest and basic control strategy is the control loop with static control parameters using only the inner loop. In this case, stability problems could take place as a consequence of environmental changes or changing plant behavior caused by different process steps.

Controller instability problems can be avoided by using variable gain controllers, which enable parameter estimation and controller adaption. Controller adaption is achieved by using different techniques. This system can use multiple information from the cutting process (cutting parameters, work piece material, tool state, etc) and based on these adjust the control parameters.

A more robust adaptive process control requires realistic process modeling and optimization based upon a good understanding of the process. Process modeling represents the link between process causes and effects. The model reproduces the reality through the relationship between process inputs and outputs in a mechanistic or empirical way. Due to the lack of mechanistic models in metal cutting, empirical models are used in this field.

2.2 Adaptive control strategies with iterative closed loop control

Very common adaption strategies found to be applied in the metal cutting industry implement actually not a continuous feedback, but instead an iterative closed loop control. These strategies used the real process state or control variable assess through the measurement system and evaluate it against the set point. When the control variable differs from the desired output, then the process parameters are changed and the process executed again iteratively until the output and the set point concur.

Three different iterative closed adaption strategies have been identified:
- Automatic closed loop with online measurement
- Automatic closed loop with offline measurement
- Human closed loop with offline measurement

In these strategies the feedback and adaption loops, found in the continuous control modes, are merged in one single loop and the adaption is based on the set point.

In the automatic closed loop with online measurement sensor systems are installed directly at the machine tool and the signals are taken during the machining process (online) and stored. Subsequently, they are analyzed and evaluated automatically by algorithms in order to determine if adjustment of the actuating variable is further necessary in order to meet the specific requirements.

Contrary to the first adaption mode, in the second one control variables are measured offline. These are evaluated against the desired output (set variable) and through algorithms the setting of the process parameters is automatically adapted.

In some cases the intervention of a human expert is indispensable for the correct adaption of the process parameters in order to fulfill the requirements.

The human closed loop with offline measurement is characterized by the complex and discontinuous correlation between the control variable and the manipulated variables. The control loop can be used for the development of machine parts and describes the iterative progress to reach prescribed properties.

3 ADACOM Control Hardware

The control hardware is the central unit being responsible for the recording and transformation of sensor signals to digital data, the hosting of the control software and the output of the manipulated variable and state information. For the connectivity of different kinds of sensors, the implementation of control strategies and the machine adequate output of manipulated variable, the ADACOM control hardware have to base on a flexible system architecture. The identified solution for the ADACOM project is a modularized architecture with slots for different input and output modules as also a high performance computing unit that can be programmed by user friendly software tools on normal desktop PC's. Caused by the status of prototyping and development and the unknown requirements with regards to the performance and connectivity, for the ADACOM case studies, the consortium used the integrated software and hardware platform of National Instruments in combination with some MATLAB programming tools of the mathworks. The different hardware systems that are offered by National Instruments are suitable for the step-by-step development from normal control loops to high performance model based control loops with hard real time requirements on the same software basis. By this, duplication of work was avoided.

A disadvantage is that the costs of the used control unit in the ADACOM project were higher as of a normal control unit in compact style. On the other hand the computing power was intentionally oversized so that the implementation of separate software modules as a data pre-processing, an identification loop, a controller and a modification loop were able without hardware restrictions. Industrial experiences in the field of adaptive metal cutting using the developed strategies will promote the standardization of flexible adaptive control systems, so that cost and function optimized compact style modules for commercial use can be designed and through this the hardware cost will decrease towards common control units. Additionally, the reduction of functionality to adaptive metal cutting control requirements in a standardized compact style offers potential to more economic and user friendly operation of the adaptive control systems. In the following some hardware architectures and their functional units of the National Instruments development platform are explained.

The desktop PC based solutions are the simplest ones in context of architecture and programming. Therefore desktop PCs are equipped with suitable data acquisition (DAQ) cards in PCI style or are connected to interface based DAQ card as the Compact DAQ solution.

The compact DAQ solution is a modular solution with the ability to combine different DAQ cards in one chassis. The advantages of the desktop PC based solutions are the minimized costs, good computing performances and the uncomplicated programming using the desktop as programming and executing target device. The disadvantage of the desktop solution is the

not available hard real-time functionality of the system. Because of that, desktop solutions are not applicable for time critical control tasks. The execution of large operation systems and software tools beside the actual control task are risky for the control task and not acceptable for time critical tasks. In the ADACOM case studies, desktop solutions were used for process monitoring and recording tasks as also not time critical control tasks in first prototype states. Especially the group of ADACOM iterative closed adaption modes is predestinated for the use of cost efficient solutions that do not require hard real time properties. The powerful computing performance of the PC solutions and the software flexibility enable a fast and comprehensive data post processing. Because of the development environment, the use of PC besides the test benches was able. For later industrial implementation, the use of network based DAQ systems will enable spatial separation of the PCs from manufacturing environment. By this, the desktop solution will be a suitable solution for the adaptive control with iterative adaption modes.
Two other modular systems are the PXI and the compact Rio platforms.

The PXI systems are standalone solutions that can be used in two different modes: Windows or hard real time. Using the Windows mode enables the programming and execution of code, but leads to loss of hard real time performance. For the execution of the real-time mode, an external PC has to be used for programming. . Exception is the use of high performance multicore systems that can run Windows and NI real-time in parallel. Advantages of the PXI systems in comparison to the desktop solution are faster bus systems and the use of rigid system-level specification that fulfill industrial standard. Nevertheless, PXI systems are not common for industrial application in rough manufacturing environment as more in test bench application. The embedded control and monitoring hardware as the compact Rio systems are designed for rough industrial environment and are designed for control cabinet installation. The systems have less performance as the PXI systems and are not as flexible regarding the choice of CPU and RAM extension. The newest systems are also able to run windows but the usual application is in real time mode.

The compact RIO system has a FPGA (Field Programmable Gate Array) integrated as standard, the PXI system can be extended with a FPGA module. In this context a gate is the electronic term for a logical switch and is used to "gate" the flow of logic in a digital circuit. The combination of gates, called gate array, produces a unique predetermined digital output state dependent upon some discrete logic input state. Field programmable describes that the array of gates may be configured in a programmatic manner and in the field, i.e. when deployed as a machine component, "in the field". These FPGA devices are manufactured and packaged as an integrated circuit in a similar fashion to that of any of the other Silicon based electronics found today. This description might well suit the modern computing machine which too are field programmable machines and execute a combination of pre-programmed logic based upon some input state. However the difference here is that the underlying transistor logic may not be reconfigured whereas in an FPGA this is the case. A combination of transistor logic may be reconfigured for the dedicated execution of some programmed logic. Modern day computers such as PCs are generally programmed sequentially, that is, each piece of logic or instruction must complete its execution before another instruction may complete execution. However, the fact that these sequential computing machines execute their instructions extremely fast and can be made to appear that many different things are happening at once, i.e. multi-tasking. In contrast a FPGA can execute as many pieces of independent logic in parallel as needed depending upon how many reprogrammable logic units the FPGA has. This is commonly referred to as the size of the FPGA and is sometimes referred to as the gate count. This term for measuring the size of a FPGA is becoming less relevant as more and more dedicated arrays of logic resource are added by the manufacturer to the FPGA as part of the overall package.

Multi-core PCs have become more prevalent but they must still use shared resources such as memory and interface busses, FPGAs may also need to share resources also of course. However, PCs are also very much abstracted from the interface hardware both in terms of the software tools used to program them and the physical separation across a myriad of interconnecting data busses. When considering the implementation of a control system using a general purpose PC architecture this has the inevitable effect of introducing latencies between an input state arriving from some sensor to the decision making core of the system and the resulting computed output state being transferred to the actuator. The architecture of the Compact RIO system does not suffer to the same extent from this latency issue. As the FPGA is connected directly to the sensor digitizing modules it can receive the sensor input almost directly and then evaluate the decision logic as fast as or faster than a general purpose computer and in turn pass the desired computed state directly to an analogue conversion module or other such actuator. The disadvantages of the FPGA are the not easy to perform floating point operations and the limitation of complexity in logic operations so that some operations have to be outsourced to the real time controller.

In ADACOM, the combination of FPGA and real time controller was identified as the most powerful hardware platform to perform adaptive strategies on continuous adaption mode. For the implementation within ADACOM, the FPGA unit is responsible for the inner control loop, the feedback loop to the process. Within this loop the sensor signals are transduced to digital data by the DAQ module of the compact RIO system. The FPGA performs the data preprocessing and executes the controller with the manipulating variable as output. By implementing this inner loop exclusively on the FPGA unit, the highest control performance can be achieved, because the preprocessing of several measurement channels can be performed simultaneous and lead afterwards directly to a control output by the controller decision. All tasks with higher computational effort as the identification of the plant, the control parameter modification and the plant simulation are outsourced to the more powerful real time controller with normal CPU.

4 Sensors and actuators (3)

In the section before, the ADACOM Hardware systems and their functionality were described. The ADACOM hardware systems include all functional hardware with exception of the sensors and actuators. For these, a separate work package was responsible to identify suitable sensor solutions, describe their properties, develop new kinds of sensor application and combination for the identification of process state and identify suitable kinds of actuate to the process.

4.1 Sensors

The ADACOM project used commercial sensors as also self-developed sensors systems for the identification of process state variables. In the following a short list of used commercial sensors is presented.

Afterwards the results of ADACOM developments of sensor systems are described.
For cutting processes, the groups of piezoelectric and strain gauge based sensors are the most common ones. In the ADACOM project the most often used sensors are the piezoelectric ones. "Kistler instruments", as project partner, is an expert in developing piezoelectric based solutions as acoustic emission, accelerometers and force dynamometers.

AE Sensor:
The used AE sensors are products of the project partner Kistler. The sensor system consists of the sensor itself and a coupler. The coupler has integrated filter, amplifier and time constant components, which can be changed by plug in. By this, the signal preprocessing can be adapted to the measurement task. The system components are changeable within the Kistler product line, interchangeability with product from other manufacturers is not known.

Piezotron Acoustic Emission Sensors with an integral impedance converter of Kistler are suitable for measuring acoustic emission (AE) above 50 kHz in machine structures. With its small size it mounts easily near the source of emission to optimally capture the signal.

The Piezotron AE Sensor consists of the sensor housing, the piezoelectric sensing element and the built-in impedance converter. The sensing element, made of piezoelectric ceramic, is mounted on a thin steel diaphragm. Its construction determines the sensitivity and frequency response of the sensor. The coupling surface of the diaphragm welded into the housing is slightly protruding to measure the AE signals. Thus a precisely defined coupling force results when mounting. The sensing element is acoustically isolated from the housing by design and therefore well protected against external noise. The Kistler AE sensors feature a very high sensitivity for surface (Rayleigh) and longitudinal waves over a broad frequency range. Depending on the chosen type a frequency range of 50 … 900 kHz can be covered.

The used AE Sensors are especially well suited for measuring in the surface of metallic components or structures. Such AE results from plastic deformation of materials, crack formation and growth, fracturing or friction. Since most of these effects occur in cutting application, AE is a common way to detect highest dynamical aspects in cutting. Combinations of AE signals with force signals for instance are very common too. Other application examples are monitoring of processes, tools and machines in metal cutting as well as forming operations.

Accelerometer:
The used accelerometers in this project are piezoelectric based sensors with IEPE standard, also called ICP standard. A common sensor setup of acceleration measurement consists of the sensor itself with integrated charging amplifier and the IEPE coupler being responsible for the power supply of the sensor. The standardization of the power supply with the IEPE standard led to the development and sell of data acquisition cards that have integrated IEPE power supplies.

Acceleration sensors are basically force sensors with attached mass. The mechanical quantity measured is force which is proportional to the acceleration, according to Newton's second law of motion. The inertia of the mass produces a force when being accelerated and this force is measured by the acceleration sensor. The relation between the acceleration and the force is determined when calibrating the sensor. The main field of application for piezoelectric acceleration sensors is measuring oscillations and vibrations on machines and structures. Several acceleration sensors were used within this project in different case studies to detect vibration in test benched and machine tools. Its capability to measure even smallest accelerations proved to be very valuable to determine the state of the machine.

The measuring element of the used acceleration sensors consists of piezoelectric ceramic in shear mode. This type of design achieves low sensitivity to temperature changes and base strain. The charge produced is converted to a low impedance output signal by an integral Piezotron impedance converter. A Piezotron coupler or an appropriate circuit added directly to the machine control system is used to supply power and signal conditioning. The rugged construction of the accelerometer makes it suitable for industrial use in severe environments that are contaminated with lubricants as they appear in metal cutting applications. As only small accelerations were expected, acceleration sensors with small acceleration ranges of a few g were used.

Force dynamometer:
The Force measurement is done with dynamometers from the project partner Kistler. The Dynamometers exist in two main variants: static and rotating dynamometers.

The static dynamometers exist in different variation and different sizes which can be used versatile for different application such as turning, drilling or other machining operations like milling. The used sensor system setup in ADACOM is modular and consists of the dynamometer itself and a charge amplifier.

During the project several different force measurement platforms, so-called dynamometers were used. All of them are piezoelectric devices. Thus, for all of them a charge signal proportional to the applied charge is generated which then needs to be converted into a standard 0 …10V voltage signal. This conversion is carried out in a charge amplifier.

Dynamometers are commonly used under laboratory conditions in academic and industry. These devices allow researchers and scientists to effectively measure forces in cutting processes in order to analyse processes. Cutting force is one of the most important physical quantity to analyse and benchmark machining processes in order to investigate cutting procedures and thus improving cutting conditions.

Dynamometers are designed to be used under harsh machining conditions in a machine tool. The characteristics of these devices and of the used piezoelectric sensors allow to measure highly dynamic forces with tooth passing frequencies of up to several hundred Hertz. Force sensors based on strain gage technology aren't able to measure highly dynamic forces as they are directly depending on the stiffness of the sensor. The sensitivity of piezoelectric sensors is independent of the structure's stiffness.

Piezoelectric dynamometers allow measuring the forces in three Cartesian coordinates. Some of the static dynamometers even allow measuring the reaction torque Mz directly, with others this reaction torque can be calculated from the force signals.

On the other hand so-called rotating dynamometers can be used too. Rotating dynamometers are placed in the machine spindle as if they are standard tool shafts. A tool is attached to the dynamometer (rotor) in a standard way. These rotating dynamometers are usually used for drilling and milling applications.

Rotating dynamometers are based on piezoelectric technology as well. A charge amplifier is built into the dynamometer (rotor) as well as telemetry electronics. Signals and power supply are transferred via near-field telemetry system which is based on inductivity. Acquired signals are pulse-mode-modulated (PCM) in the rotor and demodulated in stationary electronics.

Forces can be measured in three Cartesian coordinates as well as the reaction torque Mz. This reaction torque measurement allows to efficiently detect tool wear and chipping on the tool. Rotating dynamometers are completely independent from the mass and the stiffness of the work piece. Therefore no changes of the dynamical behavior of the system occur.

Microphones:
Measurement microphones are modular sensing devices consisting of the microphone itself, the microphone preamplifier and the condition amplifier.

This modular structure of the measurement system is very flexible and can be adapted to different measurement tasks. A common output of the condition amplifier is a signal of 0…10V and can be acquired by standardised analogue inputs of data acquisition hardware.

Temperature Sensor:
The temperature measurement is done by a measurement system of our Project partner Actarus. For the measurement system different kind of sensor designs for the processes turning, milling and drilling exist. For data transfer of rotating sensors, a telemetry system is used. The systems have a pre-processing unit with analogue signal output of 0…10V. The systems are unique prints. Because of that, no interchangeability with systems of other manufacturers is able.

Chip deflector
Within the project, a special chip deflector for the gun drilling was developed to analyze the quality of the chip transportation.

For the chip detection, AE-sensors were mounted on a deflector plate. The AE sensors detect the chip impacts (solid bourne sound). The aims were the check of continuous chip transport, rating of chip breakage / chip length, prevention of chip congestions and the gain of information for parameter adaption. In the industrial use, the system should be used as process monitoring and automatic warning system for the chip transportation state and as control system for prevention of critical chip states. In the project therefor some initial trials for the evaluation of usability were performed.

The coolant is on and the spindle is already rotating with the drilling speed. All Amplitudes have almost the same (small) value. The cumulative distribution function of amplitudes is almost linear with great slope. The lower part shows the signal of the process itself with a common feedrate. It is significant that some amplitudes are more high as in the case of using only coolant. These amplitudes represent the chip impacts. Looking to the cumulative distribution, almost 0.5 (50%) of the cumulative distribution function is the same as in the case of coolant. Over 50% the function has a sharp bend and continuous more flat. The sharp bend represents the detection barrier. This result shows that the chip detector is a usable device for the overall chip detection. Further tests concerning the detection of single chips and the correlation of the impact to the chip mass/ size were not successful. The impact of the chip depends on the orientation the chip has when it hit on the deflector and the oil that is between the chip and the deflector that is damping the impact. This results showed, that a chip frequency is detectable, but not the mass and the chip length. Therefore another kind of chip detector has to be developed.

4.2 Actuator systems:

In ADACOM it is not foreseen to develop new actuator systems, but consistently use existing interfaces and systems to initiate a machine reaction. The both most easy to use alternatives are the use of inputs of the NC controller and the manipulation of the NC code. The usability depends on the control task.

The use of NC controller inputs like the Siemens analogue modules is the option for continuous online control of the process.

Besides Siemens analogue modules, almost all NC controllers have a device for analogue inputs and outputs. Another solution is the use of digital machine interfaces.

For the use of analogue inputs, for every manipulated variable one analogue input must be defined. In the ADACOM project for example, the feedrate or the cutting speed are used as manipulated variables. After choosing the variable, the NC code must be extended by a defining function, describing, how the manipulated variable should react to an impressed voltage.

The possibility of adaptive control by changing the NC Code can be used for iterative closed control loops. The iterative closed loop adapts process parameters between two process steps or between two production cycles. This kind of adaption is possible with every NC control. For manipulation of the NC code the operator can change the code or an external NC generator can be used. The existence of machine integrated NC generators for the usage of adaptive control is not known.

The used actor mechanisms in ADACOM are easy to use. Because the actor systems do not need additional hardware with exception of the analogue modules, which are standardized for the different NC controls, the adaptive control can be implemented to nearly every NC controlled machine. This fact enables an easy and fast dissemination of the ADACOM results. Additionally, the solutions are low priced and very flexible. This makes the solutions very attractive.

5 Software

The software is part of work package 4 and includes the implementation of the ADACOM adaption strategies to real ADACOM hardware systems. The development of software includes the tasks signal analysis, feature extraction, algorithm implementation, data transformation and implementation of process monitoring strategies. In general, the software tools are all developed for the ADACOM data format which is a tdms-format of NI with defined channel and channel group properties. The data transformation software ensures that old measurement files or actual files recorded with third party equipment can be transformed and also be analyzed with the ADACOM software tools.

5.1 SIGNAL ANALYSIS, FEATURE EXTRACTION AND DEVELOPMENT OF ALGORITHMS

The signal analysis, feature extraction and development of algorithm are realized within the case study work and are connected to thematic emphasis. In the following the ADACOM development emphasis and the corresponding implementations are presented.

5.1.1 Signal analysis tool for tonal sound and vibration analysis

The emphasis "Signal analysis tool for tonal sound and vibration analysis" deals with the development and implementation of methods to analyze all kinds of vibration in manufacturing systems as also when the products are in use. Therefore a specialized software tool was programmed that includes several functionalities for time and frequency domain analysis with suitable visualization and tonal playback to support the human evaluation of the analyzed system. Within the ADACOM project the tool was used for the following tasks:

- Extraction of static frequencies and eigenfrequencies
- Analysis of speed correlated dependence of frequencies
- Extraction of speed and surface correlated frequencies
- Filter components for variable extraction and elimination of frequencies from the measurement file
- Comparison of measured frequencies with synthetic produced sound frequencies for evaluation
- Speed dependent file partition from overall measurement files
- Visualization of Results

The presented part of the GUI is the main panel for the frequency filtering and sound comparison. The upper part is the control panel with the channel and speed part selection on the left, the filter properties in the middle and the sound playback panel on the right side. The lower part presents the visualization part of this panel with the frequency analysis in the left and the gain behavior of the filter on the right.

5.1.2 Toolkit for continuous plant identification and simulation

The emphasis "Toolkit for continuous plant identification and simulation" is responsible for the basic software module of online identification that is required for the implementation of the ADACOM continuous control strategies. The identification module is part of the "Analysis system". The measurement data for the analysis are stored intermediately to a shift register, so that always the actual data are used for identification. The length of the shift register is responsible for the time that is passed in review for the analysis. The identification of plant parameters can be performed as direct identification of model parameters or a comparison model is used that is iteratively adjusted to the plant behavior by an adaption algorithm that minimizes the differences between model and real behavior. The simulation of a plant model has also the advantage of being able to predict the behavior of the plant for different manipulating variable outputs. By this, the controller can be performed with higher dynamics without running to the risk that the system gets unstable. A common solution is the implementation of a smith-predictor.

The smith predictor is a simulation of the estimated plant behavior. Therefore the simulation model is divided to the model without dead time and the dead time model. In the first step, the whole simulation behavior is subtracted from the measured signal. The result is the control deviation plus the model error. In the second step the model behaviour without dead time is added to the signal. The theoretical result is the behaviour as if the dead time does not exist. Caused by this, the control parameters can be adapted to higher dynamics.

The determination of controller parameter is done regarding the identified plant model parameters. The adaption of controller parameters allows the execution of the control with higher dynamics as if the process had to be performed with static parameters, because for that case the parameters of the worst case had to be used to ensure stability. The determination of the parameters can be performed with common heuristic methods. The disadvantage of this variant is that the heuristics most times are too conservative so that some potential of dynamics is lost. A method with higher potential is the simulation of the plant - controller system that enables the specification of desired system behaviour and determination of corresponding controller parameters.

The diagrams show the proportional factor K of the plant – controller system and the reset time ti of the controller depending on the delay time and the dead time of the plant. Knowing the proportional factor of the plant and the plant – controller system's proportional factor enables the determination of the controller's proportional factor.

In the following, the implemented tasks of the "Toolkit for continuous plant identification and simulation" are summarized:
- Direct plant identification for continuous control mode
- Iterative plant identification for continuous control mode
- Model adaption
- Simulation of plant behavior
- Prediction of plant behavior
- Determination of optimized controller parameter
- Online controller parameter adaption

5.1.3 Advanced machine and process monitoring
The emphasis "Advanced machine and process monitoring" deals with latest methods in the area of machine and process monitoring. Sub emphases are:
- Handling of large data files
- High speed real time processing using FPGA
- Position correlated process monitoring
- Network based process monitoring

The handling of large data files is done by the use of databases for the measurement files. The structure of the ADACOM used files with a header file for the channel group and channel properties allows the filtering of fundamental data properties without being forced to load the whole file. Methods for partial loading of files and channels makes the data analysis more efficient and allows fast and reliable process monitoring of different monitoring tasks without spreading time for processing data that are not used for the actual monitoring tasks.

High speed real time processing using FPGA can be done with the ADACOM compact Rio hardware. The advantages are the parallel processing of data in several gates. By this the preprocessing and analysis of several measurement channels in parallel is able so that a multiple monitoring real time system can be realized. Additional the visualization tasks and some not time critical analysis were done on the normal CPU based monitoring system. This bisection of time critical and not time critical tasks increases the reliability and speed of process monitoring systems and will caused by this raise the acceptance of process monitoring systems for the industrial use.

The position correlated monitoring uses machine integrated position signals or the direct acquisition of the position sensors. The link between the actual machine positions to the measured sensor signal enables position correlated knowledge of signal states and by this position correlated analysis of process disturbances and consequences to the work piece's surface.

The extension of the system with a position correlated simulation allows the comparison of the movement to the sensor signals.
For the network based process monitoring some special aspects of data handling like transferability of the data, transfer intervals and data size are very important. For these demands an automated data preprocessing with data reduction and extraction of key features and information are indispensable. Besides this, the safety of the system and the behavior of the system if network connectivity is out of order is a very important task. Within the ADACOM project an internet based post analysis of data that were preprocessed with an high speed FPGA in the machine and afterwards analyzed on desktop PC in office environment were development emphasis.

5.1.4 Signal analysis tool for material and tool wear differentiation
The emphasis "Signal analysis tool for material and tool wear differentiation" focused on knowledge based analysis of cutting processes. Therefore, trials were performed to establish suitable measured values, sensor combinations and process monitoring strategies. The identification of different materials is influenced by changing processing properties as example the tools wear and hence the measured values are changing. Additionally some unusual events might occur that affect the identification.

Here are the sub emphases in list form:
- Analysis strategies for material identification
- Online analysis of unusual events
- Online monitoring of process status and tool wear

The machining of different materials conducts in different values and behavior of the measured variables. There are different kinds of analysis. One option in ADACOM is the use of data bases with reference values and behaviors of different materials. Having identified the material, the machining parameters are adapted and the material is processed with the new static parameters.

Another more flexible option is based on the ADACOM model identification, (see 5.1.2). This method does not identify any specific material, but analyses the process behavior of the work piece material. By this a material property dependent adaption is able without knowing which material it really is. This ADACOM method ensures the flexibility without being forced to generate a data base before using the adaption modes and makes the solution very attractive for single item production or small batch production.

The online analysis of unusual event and process interruption is in contrast to the material dependent adaption of process parameters a measure for machine, tool and work piece protection. The focus of the research and development work was the identification of suitable sensor signals, the connectivity to the machine tool and the optimization of emergency stop times.

The online monitoring of process status and tool wear considers the gradually change of the process over a longer period and is used for the long time adaption of the machining processes, the deduction of recommendations for action especially for the shop floor employers and the identification of long time changes of the machining behavior. Caused by the amount of influences to the measurement values, the identification of tool wear is not trivial in the small batch production as even in the mass production. The emphasis of research in the ADACOM project was the identification of influences and the separation of information out of the signals to get reliable results of tool wear identification.

5.1.5 Geometric surface analysis and NC adaption

The "Geometric surface analysis and NC adaption" is an iterative approach for process design that targets the convergence of the real work piece geometry to the theoretical specification of the product.

For the realization three development emphases were performed:
- Measurement of surface geometry and digitalization
- Geometric analysis of work piece surface regarding geometric errors
- NC-code adaption with the goal of geometric error minimization

The measurement of surface geometry and digitalization targets the capture of the real surface geometry of the work piece and the transformation to a measurement file that can be used for the comparison with the theoretical specification surface. For the scanning of 3D-point clouds a 3D coordinate measurement machine can be used. The resulting point cloud is processed digitally and meshed to a surface model. The surface model can be stored in several established file format, so that a machine based application with common CAD programs can read.

For the geometric analysis of the work piece the key features of the work piece and its surface are relevant. For the geometric comparison, a CAD file with the wished geometry can be used and overlaid to the measured one. The analysis of several geometric deviations can be done by extraction of differences of the files in the specific directions. For rotation symmetric parts, the use of polar coordinate systems can be advantages.

The NC code adaption within ADACOM is done by the modification of the path planning of the machine tool. Therefore some special programs were used.

5.1.6 GUI (graphical user interface) for manual signal processing

The development emphasis "GUI for manual signal processing" dealed with the implementation of algorithms that can be performed manually to measurement data. Therefore three tasks were primarily handled:
- Extraction of channels and signal segments,
- Operation of signal analysis algorithms,
- Visualization of results.

5.2 Data Transformation Tool

In the initial situation, the project partners have different data acquisition hard- and software systems. Hence, the data acquired from the research on the case studies are stored in the specific data format corresponding to the measurement system. This high variety of data format types hinders the possibilities to exchange data between the consortiums partners.

In order that the partners can still use their data acquisition systems and the already recorded data are not out of use, in this task a software tool was developed, which converts measurement files to a standardized format and simultaneously adds a standardized documentation header to the measurement file. Additionally data plug-in are allocated to open the standardized data format with third party software suits.

The basis of the ADACOM data format is the TDMS format of National Instruments. This format enables the definition of trial properties to file, channel group and channel headers. In ADACOM the file header contains no ADACOM documentation and can be used for overall documentation if files are gathered together. The channel group header is used for the trial documentation. For the different processes, in ADACOM different forms were defined that are adapted to the needs of the processes. The channel properties headers are used for channel specific information as the description of the sensor, scaling and filtering information.

5.3 Process Monitoring Strategies

Furthermore the right strategy depending on used machine, manufacturing process and surface integrity limits is important. To get an idea of possible strategies from a general point of view, this chapter provides an overview of different strategies and possible applications. Some representative limit descriptions are listed in the following.

Overload and Underload

Static limits are applicable if the cutting conditions are staying almost constant over the process. Overload and Underload type limits set an alarm when the signal remains below respectively over a preset limit for a defined response time at least. This kind of limit is able to detect tool breakages and incorrect workpiece dimensions, for instance.

Work Over and Work Under

This limit type sets an alarm when the work value remains over respectively below a preset limit up to the end of the cycle. This type is also capable to detect tool breakage and incorrect workpiece dimensions.

Contact and Missing

The contact and missing alarm type sends out a message output as soon as the limit is exceeded. This message is reset when the signal remain s below the limit for a preset response time at least. The "Contact" alarm type detects contact between tool and workpiece and can be used to minimise machining times in air (GAP-Reduce). The "Missing" alarm type can detect missing tools or broken-off tools respectively.

Rising Through/Falling Through

These alarm types is set when a time defined limit is passed, but the signal does not pass through the limit in rising or falling mode. Time displaced signals occur for broken or shortened tools, missing tools or work pieces and incorrect tools or workpieces. This type represents just a specific monitoring of start and end of cut with tolerance of full cut.

Chip jamming or other major changes in the monitoring signal do not result in false alarms.

Dynamic Limits
Dynamic Limits above and below of a distinct monitoring signal follow the monitor signal continuously to every load level with a limited adaption speed. They may not to be confused with signal pattern or signal tube. In case of extremely fast crossing of one of the two Dynamic Limits, they are frozen (rendered static) and total breakage, breakage, chipping, workpiece cavity, hard cut interruption, etc. are distinguished one from the other via visual comparison with the monitor signal. Sudden load changes are due to total tool breakage or tool chipping.

6 Industrial demonstration

The ADACOM project had a big focus on the demonstration of the developed adaption system. Therefore the project organization was structured to work packages and case studies. The technical work packages represented in the chapters 3 to 5 are for the development of the needed components for implementation of the ADACOM adaption strategies presented in chapter 2. The case studies use the information and results from the work packages to build up single adaption systems that are used as project demonstrators and for evaluation purposes.

In the following the 10 industrial demonstrators are presented:

Milling of chain Guides – Heidelberger Druckmaschinen AG, WZL RWTH Aachen
Optimization of noise behavior of printing presses. Focus on sound emission effect caused by periodical waviness of chain guides. Finishing of the surface by end milling of cast iron chain guides. Small batch production of 10-150 parts and enormous variety of different parts. Improvement is necessary to meet the challenges of the next printing machine generation. Increasing the present margins of printing speeds of 18.000 prints/hour and chain speeds of 4.500 mm/sec.

Grinding of printing cylinders – HDM, Trinity College Dublin, Kistler
This test case is designed to implement an adaptive manufacturing strategy to empower the operator to make decisions on machine and process condition in a complex multi-step grinding process. The approach developed provides a platform for state based condition monitoring and control of grinding process and machine tools. Impacts: Reduced time to repair, improved part quality, reduced waste material, reduced operator effort and stress, predictive maintenance.

Milling of CGI – FIAT RESEARCH CENTER, WZL RWTH Aachen
Optimization of milling of truck engine block, for small batches production, of Compacted Graphite Iron (CGI450) components to be machined on the Grey Cast Iron (GCI) production line, without any change in machine tools, cutting tools and accessory systems. The objective of the work is to study the automatic adaptation of the machine tool working program parameters to support the change of the engine material from Grey Cast Iron (GG25) to Compact Graphite Iron (CGI450).

Drilling of CGI – FIAT RESEARCH CENTER, MONDRAGON Goi Eskola Politeknikoacnica
Optimization of drilling of truck engine block, for small batches production, of Compacted Graphite Iron (CGI450) components to be machined on the Grey Cast Iron (GCI) production line, without any change in machine tools, cutting tools and accessory systems. The objective of the work is to study the automatic adaptation of the machine tool working

program parameters to support the change of the engine material from Grey Cast Iron (GG25) to Compact Graphite Iron (CGI450).

Gun Drilling – Robert Bosch GmbH, WZL RWTH Aachen
The focus is the gun drilling of high-strength steels for mass production with small tool diameters (Ø less than2 mm).
Goal is the development of a system for adaptive controlling of process parameter in order to be able to react fast concerning process disturbances. Main impacts of AC in gun-drilling should be: Rapid optimization of machining process, increased tool life, improved product quality, optimized energy consumption and reduced operator effort.

Drilling and Reaming of GG25 – Robert Bosch GmbH, MGEP Mondragon
The focus is the drilling and reaming of hydraulic control valves made of cast iron with small tool diameters (less than10mm). Goal is the development of a system for adaptive controlling of process parameter in order to be able to react concerning material and geometry variation. Main impacts of AC in drilling should be: Rapid optimisation of process and adaptation to material characteristics, increased tool life, improved product quality, optimized energy consumption and reduced operator effort.

End Milling of Hardened Ring Gears and Pinions – Daimler AG, Trinity College Dublin
This case is designed to implement an adaptive strategy to enable the low batch production of complex gear geometries manufactured from conventional hardened materials, to the same standard as conventional manufacturing techniques. This will allow the development of new ring gears and pinions with optimised tooth geometries. Anticipated impacts of AC: reduced auxiliary times, improved part quality, reduced time to first part, reduced waste material, reduced operator effort, all achieved.

Milling of superalloys – DIAD, WZL RWTH Aachen, ACTARUS
Adaptive control of the residual stresses on aeronautic super-alloys parts, by studying the correlation of milling conditions with the local heating and consequently the residual stresses. The model adaption and the appropriate parameter control is realized with a combination of measured temperature and force. The difference of measured-predicted temperature is the control variable. The set point for control is chosen according to the correlation of temperature and residual stress measurements.

Drilling of superalloys – DIAD, MONDRAGON, ACTARUS
Adaptive strategy for the control of the residual stresses on on aeronautic superalloys parts machined parts, in term of study of the correlation of drilling conditions, with the local heating and consequently the surface and sub surface defects. Main aim of the Adaptive Control model developed by MGEP is to keep temperature constant in drilling process by actuating on drilling parameters, in particular the feed rate.

Milling of composite – LOLA, TEKS, Trinity College Dublin, Actarus
This test case is designed to implement an adaptive manufacturing strategy to characterise and control the cutting of composite materials. The approach developed provides a platform for monitoring of temperature, consideration of forces and examination of tool workpiece interaction leading to chatter. Anticipated impacts: reduced machining time, improved

part quality, reduced waste, reduced operator effort and stress, first of a kind temperature data on composite machining.

6.1 Milling of chain guides

During the manufacturing process for chain guides inside the delivery unit of a sheetfed printing press a characteristic topography occurs. The aim is to analyze this topography and to identify a milling strategy which reduces the periodical waviness and improves the working conditions of the printing press.

For the development an alternating approach of surface preparation and surface in use analysis is needed. The missing of automated software for the sound analysis of human noise perception makes the intervention of a human expert until today indispensable. Caused by the stepwise approach and the expert's intervention, the iterative adaption strategy "human closed loop with offline measurement" was chosen.

The extraction of the noise source by a chain guide model and the implementation of the relative movement between chain and chain guide to the test bench #1 enabled the case study team to investigate in different surfaces. The detailed sound and vibration analysis lead to the knowledge of parameters that are decisive for the sound generation as feed rate per rotation, runouts of the tool and periodicity of the surface structure.

Therefore the following software implementations were used:
- 5.1.1 Signal analysis tool for tonal sound and vibration analysis
- 5.1.6 GUI (graphical user interface) for manual signal processing

Afterwards the surfaces with improved noise properties were evaluated in the test bench #2 that represents some original mechanical parts of the printing machine's delivery unit.

The upper signal shows the results of a chain guide in use that was prepared with the standard milling parameters and an additional chamfer 0,5 x 45°. The colours represent different relative movement velocities. The dependency of stimulated frequencies is clearly shown. The comparison of relative velocity and stimulated frequency lead to knowledge that the milling feed rate per rotation is responsible for the stimulation frequency. The challenge of solving this problem was the modification of the milling process without getting out of economic range. A change to alternative processes is almost not able caused by the free from geometries and the high production specification. At the end of the project, the case study partners were able to identify an alternating milling strategy with an oscillating feed rate implementation. The lower diagram shows the FFT of the new ADACOM milling strategy that conducted in an avoidance of specific frequency stimulation.

In the end with the adaptive strategy developed in ADACOM the excitation of tonal noise was reduced tremendously. The excitation of the frequency caused by periodical waviness as well as the frequency of the sliding mode can been seen. Both effects were reduced especially the effect of periodical waviness.

6.2 Grinding of cylinders

A significant part of the printing machine success in operation is based on precision manufacturing of large components as seen below. In today's production, HDM has to face reworking and rejection costs due to "scattering marks" on the cylinder surface. It is a highly sensitive process, which results in off-times of the machine caused by time required for diagnostics and error detection. In the grinding process of steel cylinders all previous activities have been internal meetings with partners from a broad range of experience such as internal grinding experts, sensor manufacturers and colleagues from the research and development department, hence a project team within HDM was established at the initial stages to support the technical work on the project. One focus was the development of approached towards process comparison and documentation of a stable process to a process with scattering marks to evaluate specific error charts.

The aim was the reduction of off-times of the machine due to quantification of critical influence parameter of machine tool components. To define the adaptive control system boundaries, inputs and outputs, two case studies have been defined:
- Polygon grinding of plate cylinder G2.007.001 (heat-treated steel Ck45) on Schaudt PF61
- Grinding of printing cylinder F2.011.101 (grey iron GJL-300) on Naxos PMDS720

In a workshop with partner TCD and internal experts the case study description and the next objectives have been defined as shown below.

Approach and development strategy
Following various face to face meetings and phone conferences between the TCD and HDM teams, a proposal for in-process-measurement was presented by TCD and discussed with experts from HDM. The proposal was developed taking into account the developed 3D-model, the support of Kistler sensors and HDM production requirements and limitations and this work was undertaken within WP2 and WP3. On site investigations took place on machine tool Schaudt PF61. Data recorded from vibration sensors installed in the machine tool show that the features of the grinding process are evident and form the basis for in-process quality assessment.

The grinding of printing cylinders is a complex manufacturing process due to the number of steps in the process chain and the complex couple between axes movements in the machine tool. As part of the implementation, a development DAQ and plug-and-produce measurement chain was developed and remained in the machine tool for extensive periods of time while data was transferred via fp. A further notable step has been the testing of the transferability of the ADACOM solution from one machine tool to another in effect testing the concept of modularity, flexibility, and standardisation proposed in WP2.

It can be seen from the closed loop adaption mode that the high speed parallel processing capability of FPGA's is used to interpret the vibration data and undertake feature extraction. A main technical development in the HDM case is the state based analysis approach which was enabled through the extensive acquisition capabilities of the C-RIO standardised system.

It can be seen that the GUI is based on the vibration intensity on the surface of the workpiece as well as limit based interpretation of the levels within specific states and operates online in real time. The full solution was demonstrated at the 42 month meeting and has been exploited with TCD/HDM to remain in place in the HDM facility following the project.

An example of standardisation and modularisation of the hardware from WP2,3 and software WP4is also highlighted in the HDM case. A similar system with some additional features was developed and implemented on a NAXOS machine tools. In this case the wireless vibration sensors were installed as the axes travel in the machine tool is significant and presents many challenges for signal cables. The work undertaken on the NAXOS was proposed as proof of principle and this was used as a demonstration for the 42 month meeting in HDM in April 2012.

The demonstration of the two ADACOM solutions working in production took place in April 2012 and it could be clearly seen that the ADACOM project has delivered proof of concept applications. Full operator training, training materials and operator manual was developed and provided to the HDM personnel and this case highlights a full technology transfer/exploitation of the adaptive control system to the industrial partner.

6.3 Milling of CGI

The good mechanical and thermal properties of Compact Graphite Iron (CGI) continue to motivate the development of applications of this material for internal combustion engines. The process adaption is intended to support the change of the workpiece material from GG25 (Grey Cast Iron) to CGI, at the same boundary conditions (machine and cutting tool) by the adjustment of the machining parameters dependant on the material and tool condition.

The challenge is to develop a flexible production system that is able to rapidly shift the machining conditions (adapting machine parameters) when the component material is modified. With the same boundary conditions, such as tools and machine, the systems will be able to adapt the working parameters to the workpiece's material response based on the spindle power.

Evaluation of the process monitoring and control hardware was done at WZL. Process monitoring software-machine tool communication was achieved for the actuation of the spindle and feed drive. Independent hardware for process monitoring and actuating systems were defined (chapter 4). Since difficulties in the material identification were found, the goal of power minimization was discussed as another focus for the control.

In the sensor actor system, a force dynamometer acquire the effective power of machining and the actor uses digital machine interfaces for parameter adaption. The adaption required is the variation of machining parameters (i.e. feed rate) to adapt the power consumption to the working conditions. The parameters for evaluation will be productivity and workpiece final quality. For the balancing of energy absorption with changing cutting parameters when working different strength materials, the evaluation of a mean cutting power model has been done.

For this case study the Model Based Continuous Control Mode was used; it considers the parameter and process model adaption. Furthermore this model is used for the calculation of set-points and specification of control limits that cannot be exceeded.

A modular platform (FPGA) for the acquisition of process signals and machine actuation was installed in order to replace hardware used in the first testing phase.

The control algorithm was developed and programmed in LabView.

First testing of the algorithm for feed rate control and material identification was done. Further testing and verification of adaptive control system performance were done later.

A modular FPGA platform has been installed on the demonstrator machine at WZL for the signal acquisition and actuation of the machine tool. Model based algorithm was developed for the feed rate control and material identification in milling and then the Integration and first testing of NI LabView software, FPGA module and machine tool system succeed.
The tests carried out in WZL were implemented in a "experimental" production environment using the resources of the Advanced Machining Laboratory located in CRF.

The Comau Urane 20 represents a module similar in all its part to the machines present in Fiat production plant During the preliminary work, the tests conducted in CRF defined CoroMill R365 Sandvik Coromant as the insert selected in specifically designed for working CGI and it is already use in various industrial processes.

Assuming the main parameter of evaluation for considering different machining behavior the power consumption, final experiments considered both continuous and interrupted cut. For the shift of machining conditions depending on the material (GG25 or CGI) it has been found that the effective power provides accurate information compared to the torque acquired with piezoelectric dynamometer about the cutting power depending on the material. Given that the effective power can also be easily measured in industrial applications through hall-sensors and different modules, this signal has been selected as appropriate for the machine tool control in the industry. The mechanical power signals acquired increase proportionally with the cutting speed. The effective power needed for machining CGI is higher than the power required for GG25. Required mechanical power is also directly related to the cutting parameters (Fz and ap) with a linear increment. For different cutting speeds, the tendency remains equal but the power level varies.

In the second step work, after the two materials have been differentiates, the main aim is to define the changing strategy and its feasibility. The goal of the control is to keep constant power consumption through variable cutting conditions and to monitor tool wear and possibly interrupt the process. The control model developed is "model based". The prediction of the necessary power uses a mechanistic method that assumes that the cutting forces are proportional to the cross-sectional area of the uncut chip. This relation takes into account geometrical characteristics of the process and empirical specific cutting coefficient obtained from experimental work that characterise the tool-workpiece couple . The mechanist model developed by Kienzle uses potential approximation and is a function of the area of the uncut chip that is divided in two terms: first one is linear that takes into account shearing mechanism and the second one is a potential that consider friction, rubbing and ploughing effects.

The upper figures show higher power consumption for CGI450. The lower graph shows the relationship between power consumption and cutting speed (Vc) and feed rate.

The definition of the control loop requires the setting of some constraints and boundaries: the maximum mechanical power is set at Pmax = 2.5kW. The tool wear limit is set at 0.25 mm. The model developed is not based on the prediction of the cutting forces but on calculating the mean power based on chip thickness in order to differentiate the materials.

The machining of GG25 requires less power than CGI. However there is an overlap range dependent from the cutting parameters. Therefore the use of the specific cutting force should rather be used for the identification of the material. However it was observed that specifically for the cutting speeds selected to machine the materials, there is also an overlap in the specific cutting force values. The major problems of this model are given by the overlaps due to tool wear (that evolves in different ways depending on the material) and material conditions. Therefore a range for K that takes into consideration both tool wear and material inhomogeneity should be determined.

Still regarding the second step work, the optimisation process to find the model parameters that best fit the data required a bigger sample of data and some other experiments to be done by CRF. In this phase of the process CRF has carried out in-house tests on milling CGI and GG25. The main goal of the experiments was to acquire the power consumption data of the machine tool while working both cast iron materials. The machine used for the tests is the Comau Urane 20.

The mill is the same used in the tests at the Aachen University: 5 teeth and 50 mm diameter Sandvik mill, with Sandvik CoroMill 365 inserts. The power acquisition was made by using a Fluke 435 II Power Quality and Energy Analyzer connected to a data acquisition system.

The power acquired is only the one required for the cutting process, so the idle power has been subtracted each time. The experiments were conducted setting constant the depth of cut and varying the feed rate. The tests considered two different conditions of engagement of the tool: one with ae= 9 mm (one tooth machining) and the other with ae= 50 mm or the entire mill diameter (five inserts working simultaneously). Three runs for each set of conditions were performed on the same plate.

The results were acquire and analyzed, then compared with the data obtained by WZL. Using the Kienzle formula, the data collected make possible the definition of ranges of values valid for both materials and boundaries in order to differentiate the two cast irons.

The results show some incongruities with 50mm tool engagement, especially at the highest feed rate and working CGI. However the overall data are in line with those obtained by WZL and will be used for better calculation of the constants.

The milling case study has given so far encouraging results. The first step work confirmed that it is possible to recognize the type of cast iron which is been working on the basis of the energy required by the process. Second step work developed the model based control system with significant results in the design of a power model for milling. The next challenge will be the changing of the model parameter according to tool wear: investigation and recalculation of specific cutting force during the process in order to take into consideration the tool wear.

The adaptive system seems to effectively close the control loop in short times and the interfaces between computer software and the machine do not represent a delay. The control loop is capable of yielding good benefits to the machine tool functioning. It looks like it is possible with a common system of power acquisition to differentiate the cast irons and adjust parameters as the feed rate to keep a constant rate of power consumption.

It is believed that the changing work strategy is feasible and soon 'exportable' to an industrial production environment for further analysis. The software tool developed by WZL can be exported on other machine tools adapting it to the new machine and different sensor and positioning. Therefore, the third step work will involve the testing of the adaptability of the adaptive system to production. Benefits in terms of productivity, cost efficiency and resource saving are expected from this system but this has to be proved by further critical validation outside laboratory conditions.

6.4 Drilling of CGI

Drilling tests were carried out in the laboratory for High Performance Cutting of the Engineering Faculty of Mondragon University. The main requirement of a sensor-actor system was the acquisition of the power consumed by the spindle and the action through parameter changes in machining program.

During the preliminary work, tests carried out in CRF defined the type of drill to be used in the machining operation. The drill selected is a special type 6,8 Gühring R-RT1 R designed for high strength CGI that can be used also with other cast irons. Two types of this drill were tested in MGEP: without coating and with FIREX® coating (TiAlN+TiN multilayer combination).

National Instruments software, Matlab, has been used to acquire and store data. All data are stored in the TDMS (Technical Data Management Streaming) format which has been proposed as the standard data storage format for ADACOM. The software on the machine tool is a Fagor CNC 8070.

The first step work was based on tool life tests with both drills on CGI and GG25 plates (dimension mm 250 x 250 x 50) and measurements with sensors on a separated specimen. The monitoring was performed using a dynamometer (Kistler), an acoustic emission sensor (Bruel and Kjaer), a termographic camera (Titanium series) and an accelerometer (Bruel and Kjaer) (Chapter 4).

The unsatisfactory results, according to MGEP, may be due to differences in hardness of both materials. Subsequent hardness tests on different points of used and not used plates showed that there are big differences from values registered on the same plate. Hardness of a plate of CGI is in a range between 195÷213 Hardness Brinell (HB) while GG25 ranges from a minimum of 183 HB to a maximum of 229 HB. The big range of hardness may be one reason for the overlaps of the acquired signals of forces, torque, acoustic emissions and vibrations. Overlaps may be given by drilling one area of a plate of GG25 whose hardness value is bigger than the highest value registered on a CGI plate. When this happens, the signals acquired of force, torque, AE etc. for GG25 will be higher than those of CGI, creating overlaps and making difficult to differentiate the materials.

Subsequently, CRF carried some in-house tests on the hardness of the two materials. In particular, a metallographic analysis of CGI and GG25 has been carried out and the hardness results have been compared to the ones obtained by MGEP and the specification of the foundries providers of the plates. According to these tests the average values of hardness are 210 HB for CGI and 227 HB for GG25. From this analysis it is possible to see the characteristic structures of the two cast irons. The structures of the two cast irons reflect their chemical composition and the material can be considered in good conditions for experiments as they fulfill the specifications of the provider. It is confirmed that, given the good conditions of the plates supplied, the recognition of the two materials in drilling, would be difficult considering any given component of CGI or GG25.

Regarding the development phase, the results obtained did not fulfill the requirements. In order to complete the first step work it is required to execute other experiments for at least obtaining satisfactory results about the differentiation of materials.

One solution proposed by CRF suggested repeating the experiments with another tool. The suggestion is to use a generic drill Gühring RTU type, instead of RTR type which is specifically designed for CGI. A different geometry tool with generic good performances when machining cast irons could show more difficulties and tool life problems when machining CGI. The use of this new tool could enhance the difference between acquired signals (axial forces, torque, vibrations etc…) and make easier to differentiate materials. In addition, the proposal includes the inclusion of a temperature sensor provided by Actarus into the drill, in order to try at least, to differentiate materials on the basis of the temperature signals.

However, CGI 450 grade, typically used in engine block production, gave, among others, surprisingly results, combining high mechanical performances of compacted graphite iron and machinability similar to common gray iron. Cutting forces were calculated determining the Kienzle equation constants and exponents, showing very small differences for the two materials.

These results are promising for the use of compacted cast iron in productions but confirms the poor outcomes in the case study of the efforts done in order to differentiate materials.

It is important to carefully choose the composition and the characteristics of the compacted graphite. CGI machinability can be very similar to GCI, especially in drilling processes. Further tests on real industrial components might show that differences are higher than the ones acquired in a laboratory test bed.

However, the results obtained in this first phase of the case study are critical in order to pass onto the next stages and achieve the development of an adaptive algorithm. Therefore it is important to carry out more experiments to gather significant data to solve the control problems and, possibly, reach the definition of a unique algorithm and a solution for the CRF case study.

6.5 Gun Drilling

Only non-controlled gun drilling processes are used currently in mass production of fuel injection systems. Because of decreasing drilling hole diameters and the usage of steel materials with higher strength and higher hardness for new generation of fuel injection systems those traditional gun drilling processes reach their technical limits. In order to increase the process efficiency and to decrease the amount of process disturbances and machine breakdowns an adaptive control system for gun drilling processes with small tool diameters is needed. Additionally, the most suitable process monitoring systems have to identify in order to integrate into such an adaptive control gun drilling process.

For development of an adaptive-controlled gun drilling process the work was focused on three main activities: determination of gun drilling process behavior and characteristic process phenomena, testing different sensor systems in order to identify the most suitable ones, and developing the close-loop software system as well as building up the hardware components for the adaptive-control system.

As approach for a closed-loop system the simplest and basic control strategy with static control parameters using only an inner loop proved to be most suitable for the application gun drilling. Also the axial process force Fz was identify as best monitoring and control parameter. As adaption parameter the axial drilling feed rate was determined. This parameter can easily adapted by the feed override of the NC control of the gun drilling machine. Therefore a Siemens analogue module was used for the continuous input to the NC controller. In the figure below the complete developed close-loop control approach for the case study gun drilling is shown.

In order to monitor the control parameter axial process force with a high dynamic and a high sensitivity the usage of a static dynamometer with a charge amplifier from the project partner Kistler has proven to be most suitable. This static dynamometer was mounted behind the workpiece clamping system to avoid dynamic disturbance coming from the high rotating speed of the drilling spindle.

To analyze the measured drilling force and to calculate the current needed drilling feed rate the software part of the adaptive-control system was developed in LabView8.6 from National Instruments. This software tool was most suitable concerning free control-program design and implementation into laboratory environment.

In the first half of the project BOSCH was studying gun drilling process behavior and characteristic process phenomena like tool wear, chip formation, process forces etc. depending on variation of process parameter and material hardness. At the same time WZL Aachen was developing, building up and testing the first prototype of the adaptive-control system. In the second half of the project the adaptive-control system was implemented into a gun drilling machine at BOSCH laboratory for close to production studies. Furthermore, the adaptive-control system was optimized and further sensors for monitoring were tested by the WZL Aachen.

After the integration into a gun drilling machine the adaptive-control system was tested within different experimental studies in order to determine the working range, the advantages and the impacts. The tests showed very clear the differences between a gun drilling process without AC-system and a gun drilling process with AC-system. Standard non-controlled gun drilling processes are characterized by process disturbances like chip jamming. If the drilling operation was done with a new gun drilling tool only a small number of disturbance could be detected by axial feed force monitoring; if a worn gun drilling tool was used the drilling operation was characterized by a high number of disturbance as well as sometime the process has to be stopped because of heavy chip jamming. In contrast to that, during adaptive-controlled gun drilling no significant process disturbance was detected. The tests showed also that the parameters for the AC-system have to be chosen very sensitive. Unsuitable control parameters cause high dynamic process behavior of the AC gun drilling process. Only by control parameters which are adapted to the special condition of each gun drilling application a robust drilling process could be realized. Depending on the machined material the process disturbances and the level of reduction by the adaptive-control system varied. In contrast to non-controlled gun drilling processes which showed critical process disturbances like machine breakdown and tool brake these showed critical process disturbances could be avoided completely by using the adaptive-control system.

Furthermore, the study on tool life showed that by adaptive-controlled gun drilling the tool life of the sensitive gun drills could be improved, but the trend of decreasing tool life was still determined if the workpiece material hardness was increased. Nevertheless, a reduced tool wear means an increase of production output per drilling tool and finally an increase of economic performance of the gun drilling process.

Summarizing the obtained further results can be descript with the following main impacts: Depending on the chosen adaptive-controlled force level the cycle time could be reduced but by increasing the adaptive-controlled force level the tool wear also increases which means the tool life decrease significant. Consequently, for each gun drilling application a process optimization has to be done in order to make a compromise between cycle time reduction and increase of drilling tool life. Varying process force leads to a dynamic feed rate adaption during gun drilling. This affects finally the process (cycle) time, but the determined deviation of process time is quite low by adaptive-controlled gun drilling which means the process stability is quite high. This is a satisfying result under the focus of integration into mass production concepts. Furthermore, by adapted-controlled gun drilling the surface quality of drilling holes could be improved. The results showed a reduction of surface roughness of about 30% which should mainly caused by the reduction of process disturbances.

The conclusion at the end of the project is that development of an adaptive-control system for gun drilling was very successful concerning all aspects of industrial requirements in this case study.

6.6 Drilling and Reaming of GG25

The focus of the work was to develop an adaptive-control system for machining processes with small drilling and reaming tools (less thanØ 4 mm) in order to increase the process efficiency and to decrease the amount of machine downtimes. Only non-controlled cutting processes (drilling, step drilling, milling, tapping, reaming) are used currently in production of parts made of cast iron for industrial applications, for example housings of hydraulic systems. Caused by the casting process the iron material shows inhomogeneities and varying part dimensions (large fabrication tolerances). Also this manufacturing sector is characterized by the demand of high flexibility because of large part variation and small batches. Consequently, the range of tool geometries and cutting process condition is very large. Currently, there is no suitable adaptive system or even a monitoring system available for the multifaceted machining process of components made of cast iron.

Starting the development work with the focus on basic drilling studies and testing of suitability different sensors, a first prototype close-loop control system was build up. The results of the basic drilling studies showed that there were no critical process states or characteristic process phenomena which lead to critical problems concerning the automatic adaption of the process. One of the big challenges was the reliable and sensitive process monitoring for input data for the adaptive-control system. Unfortunately the best-way monitoring system, the measurement and analysis of the spindle power which was used for the first prototype adaptive-control system showed a low sensitivity and a long reaction time. Here for the small tool diameters and small cutting depths this monitoring system was running at its limits. Consequently, high-resolution piezo-measurement equipments from the project partner Kistler showed to be a better monitoring system. Besides the use of a static dynamometer, finally a rotating dynamometers was used for tool sided measurement of force and drilling torque.

The analysis of the adaption requirements of this cast study lead to the development of an approach of a closed-loop system with a control strategy of static control parameters. This control strategy in combination of using drilling torque as control parameter proved to be best for this application. Also as adaption parameter the axial drilling feed rate was determined. In order to adapt this process parameter a C-program subroutine was added to the main PLC program which gets its input data from a PC-based analyzing module. This analyzing module is made on LabView and Matlab software. The hardware components for collecting and amplifying the measurement signals are all National Instruments hardware which was chosen as standard components within the project.

After the iterative optimization of the adaptive-control system the new drilling performance as well as the advantages and the impacts were investigated. Therefore different experimental studies were done and compared with standard non-controlled machining processes.

First step was the verification of the increase of performance by drilling tests with different drilling tool states. By increasing of tool wear the process load is also increasing. Consequently, the drilling performance has to decrease in order to keep the tool load constant. The adaptive-control system was exactly reacting on the process load changes depending on the tool wear. The drilling feed rate was automatically reduced in order to keep the tool load constant until the set lower feed rate limit was reached.

The adaptive-control system also reacts successful and sensitive if the drilling tool was machining an interchamber of the cast iron workpiece. The axial feed rate was rise up to the set maximum speed limit until the monitoring sensors detect the end of the interchamber. By this strategy the machining time for cast iron parts could be reduced compared with the traditional non-controlled machining processes in current serial production. The advantage of the adaption-control system here is that no information about the position and the size of the interchambers is needed. So the adaptive-control system is working independently from workpiece specification, a high flexibility for use in small batch production is fully given.

Another important aspect was the influence of the adaptive-control system on tool life. The results of the experimental study showed clearly that there is a positive effect on tool wear behavior. By adaptive-controlled drilling the tool wear could be reduced significant and the tool life could be increased in average about 50% compared to non-controlled drilling processes.

Furthermore, the drilling tests showed that by adaptive-controlled drilling of cast iron the machining quality can be improved. A better surface roughness Rz was determined compared to non-controlled drilling processes. As reason for this results the more constant process conditions were seen which lead to a better cutting process and hence to a better machining quality. Besides tool life, tool wear and surface roughness further aspects of the drilling process of cast iron like energy consumption, cycle time and geometrical quality were also analyzed. The experimental study showed mainly better results if the adaptive-control system was used for the drilling process. Only the energy consumption and the cycle time showed sometimes marginal higher values. The higher energy consumption was caused because the machine axis had to do more acceleration due to the adaption of feed rate. Higher cycle times were the result of the adaption of feed rate in order to keep the torque load constant if drilling solid workpieces. By increasing the torque load level for the adaptive-control system a reduction of process time could be realized and the seeming disadvantage of higher cycle times during this experimental study could eliminated.

In summary, an adaptive-control system for the drilling process of cast iron with small tool diameters was successful developed, which is able to adapt fast machining process parameter even if the process changes, for example increase of drilling torque because of tool wear, are quite small. Also this adaptive-control system enables an increase of manufacturing quality and an increase of productivity because of longer tool life and in consequent of that a less number of tool changes and machine downtimes. Furthermore, the possibility of cycle time reduction is given by optimization of torque load level and by using the adaptive-control system for machining interchamber workpiece. This fact will also lead to an improvement of manufacturing efficiency for small batch production lines.

6.7 End Milling

The goal of this work is to end mill hardened spiral bevel gears with free form flank surfaces using a 5 axis machining centre. With traditional gear manufacturing methods, the purchase and tooling cost along with the expertise and time required for setup of every gear geometry type makes the gear generation method worthwhile only for mass production. The low quantities required for experimental validation purposes do not justify the expensive, complex machining solutions offered by many specialist gear manufacturers aimed at high batch production. This work is being realised alongside the development of a spiral bevel ring gear and pinion with optimised new tooth geometry. The spiral bevel gears machined during this research are designed for use within the rear differential of some Mercedes Benz vans.

The advantage of the new tooth geometry is mainly in efficiency improvement, and can be broken down into the three following points:

- A decrease in fuel consumption connected with reduced CO2 emissions
- Increase of the power density of the gear, including higher torque and a reduced space
- Good NVH (Noise Vibration Harshness) behaviour

Approach and Development Strategy:
The approach of the test case involves three main steps. These are:
- Step 1: The mathematical definition of the required gear geometry (Daimler internal project)
- Step 2: The validation of suitable machining technologies and manufacturing methodologies to allow precise gear prototypes to be manufactured for test runs (Test case work within ADACOM)
- Step 3: Small batches (10-20 parts/lot) manufactured with the developed machining technology and manufacturing methodology

The 'State of the Art' through ADACOM involves a full description of the machining process and parameters, as well as a deeper investigation of the form and position errors of the produced gear using CMM technology. The understanding of the errors and error sources allows for the adaption of the 5 axis machining process in order to achieve the initial aims of the project.

Details of Technical Developments
The main strategy used in this case study involves the utilisation of three adaption modes, an iterative closed adaption mode using offline tactile measurement based on the Zeiss UPMC Carat 850 CMM to adapt flank form and position errors, an adaption loop for the homogenisation of tool wear via tool contact point adaption (TCPA) to increase process robustness and repeatability, and virtual metrology techniques to identify sources of machining error to allow for workpiece and coordinate centre adaption. The inputs to these adaption modes are based on offline measurements.

One of the main adaption modes utilised during the project is tool contact point adaption, or TCPA. This involves the continual adaption of the tool axis and depth settings in order to ensure that a no portion of the tool contacts the workpiece surface more than once during a milling operation.

These hardware tools include the Kistler Rotating 4-Component Dynamometer with Multichannel Signal Conditioner for force measurement during machining, and the Deckel Maho DMU 100P 5 axis machining centre.

The main software developed during the Daimler case study is the so called 'NC-Generator'. As a general overview, the aims of the self-developed NC Generator can be described as 4 fold:
1. Generate 3 and 5 axes NC code based on ideal part point coordinates,
2. Adaption of said NC code based on measurement results from a CMM (compensation of machining deviation),
3. Analysis and smoothing of the shape of the tooth flank,
4. Producing visualisation algorithms for ParaView and Catia.

The overall purpose of the NC generator is to generate NC and APT code, based on a discrete description of two almost rectangularly opposed surfaces in 3D space, for the purpose 5 axes simultaneous flank milling of those opposed surfaces. The NC Generator then allows for NC code adaption to adapt for machining errors, in conjunction with the offline coordinate measuring machine measurement results of the measured parts.

Results achieved through ADACOM

To achieve a manufacturing process which is repeatable and reproducible, it is critical to understand the sources of error in the process, so that they can be eliminated. This includes the development of suitable milling strategies on 'soft' material, and transferring these techniques to hardened steel (HRC 62), the switch from point to flank milling, the redesigning of clamping units for both pinions and ring gears, the development of the AC modes, the development of virtual metrology techniques, the development of measurement strategies and the switch to a new, more modern 5 axis machine tool, the Deckel Maho DMU 100P. These developments have had an extremely positive impact on the overall quality of the gears, rated as DIN values, the surface quality of the flanks, the flank topography, the tool life, and the running transmission errors of the gear sets. In all these areas, the gear sets produced today through the ADACOM 'state of the art' process surpass those produced via the series process, fully validating the developed machining methodologies. The time to first part has also been vastly reduced since the beginning of the project, with all first parts created through the new strategies being correct. This represents a significant advantage over the series process, and has the potential to lead to great time savings in comparison.

6.8 Face Milling of Super Alloys

During the manufacturing critical rotating parts in the aerospace industry, the resulting surface integrity is of major importance as it influences fatigue life and hence safety of the product (and consequently aeronautic transportation). Finishing cuts on turbine and compressor disks are in general a critical operation for surface integrity. Milling and drilling operations are critical and sensitive processes due to difficult cutting tip engagement, interrupted cuts and unfavorable heat dissemination. Methods for ensuring sufficient surface integrity nowadays are not flexible and productive enough to meet the challenges of the future. The aim of this case study is the definition of an adaptive strategy for the control of the residual stresses on machined parts, in term of study of the correlation of machining conditions, with the local heating and consequently the residual stresses.

Materials applied for aero-engines turbine and compressor disks are Ni based super alloys and Ti alloys. These materials have a strong tendency to strain hardening and heating generation during cutting: the consistent local heating can leave abnormal residual stresses on the aero-engines parts, decreasing their fatigue resistance at operative conditions (high temperatures). In this perspective, an adaptive machining strategy controlling residual stresses would have major impact on robustness and performance of the production processes.

Contributions of the adaptive system to the generic system include the adaptation capability of feed, speed and cooling condition. The adaptation modes used in this work include:

- Adaptation of parameters: cutting feed and speed
- Adaptation of machine state: cooling condition

The experimental activity has been carried out by following steps:

- initial trials of a first set of tools and cutting parameters, in order to ensure a sensible choice of tools and parameters.

- residual stress measurements and Process Monitoring, in order to constitute a data base for subsequent development of control strategy for case study.
- Main focus on finish milling cut. Only in a second phase the methodology has been extended to drilling, because of the complexity of this operation and the difficulty to measure the residual stresses inside the holes.

A dedicated milling test bench has been created in WZL.

The sensors configuration for milling was composed by: Temperature Measurement System Actarus implemented on the tool holder and the inserts, Acoustic Emission Sensor Kistler 8152A211 and a 3-component-Dynamometer Kistler 9255B mounted on the workpiece fixturing system. Calibration tests were conducted on temperature sensors, confirming that the measurements were reproducible and reliable, the influence of heat source location on the cutting edge was negligible. A comparison of measurement by Actarus sensors and by thermal camera confirmed good agreement in dry cutting, whereas in case of cutting with coolant the sensitivity of the system was too low.

Determination of stable cutting parameters has been done starting from the production cycles generated from dedicated design of turbine disk. Different finishing milling radial depth and axial depths have been tested doing measurements of cutting forces and acoustic emissions. The chosen parameters, tool and workpiece given force and acoustic emission measurement yielded reasonable results during the trials.

Acquisition of process monitoring data to validate chosen models. Results for model validation have been achieved (results for different combinations of radial and axial depth of cut). For temperature prediction, available models have been taken into account and implemented in LabView. The available models use the force signal as input, furthermore assumptions for shear angle and contact length must be taken.

Creation of a data base for prediction of residual stresses. It has been decided to correlate the process monitoring signals to the residual stresses using statistical methods. In order to be close to real industrial conditions, the influence of the position on the part (tool entrance, steady cut, tool exit) has been determined randomly. Many cutting trials (by interrupted turning) have been performed in WZL, the PM signals and residual stresses measured, correlated and used for the constitution of the statistical database.

Continuous Parameter and Process Model Adaption. The force data has been used as input into the model online, whereas the modelling of residual stresses was empirically determined based on temperature, as a function of parameters. The temperature can be predicted using the data for force in an expanded Jäger model (model from Komanduri and Hou). A model structure based on temperature input and speed modification has been developed introducing a Model predictive control for temperature prediction in order to increase the reactivity of the adaption. The Model predictive control (temperature) is composed of these phases: definition of reference trajectory, prediction of control variable with the help of the process model dependent on actuating variable and disturbances, comparison with actual process information for realistic prediction, definition of a cost function to reach control objectives, optimization of actuating variable at each sample and hold circuit (receding horizon).

The advantage of this approach will be the calculation of actuating variable based in minimizing of cost function ("Online"), the explicit definition of limitations for actuating variable, state variable and control variable, the inherent compensation of delay time and the direct integration of disturbances. LabView has some of the functionality in order to minimize the work of coding and to allow for implementation.

Development of adaptive control for production machine. For the prediction of the temperature an explicit model has been used, where the cutting speed serves as major manipulated variable.

The adaption of the model and the appropriate control parameters is realized with a combination of measured temperature and force. The difference of measured and predicted temperature represents the control variable. The set point for this control variable is chosen according to the correlation of temperature and residual stress measurements.

The software tools used for data acquisition and storage for the trials were standard software programs (VIs-Virtual Instruments) from National Instruments' software LabView. The data analysis was done in appropriate software Diadem connected to LabView. For the implementation of the control on the machine also LabView VIs will be used, for the proposed model predictive control software solutions are provided from National Instruments. For the thermal sensor, ACTARUS developed a specific routine simple within the TWS software called "Fonction Sortie" (S, EXP) which enables to send on the output channel a mathematical function "EXP" calculated from a sensor data (ex : input is "Volts" and output is K x "volts").

In conclusion the three major technical tasks were the development of a temperature model, the definition of the set point and the implementation of the control on a production machine.

The simplified temperature model based on physical fundamentals works sufficient for application aerospace application (-greater than limitied parameter window).

The definition of set point for residual stresses is difficult
The implementation of the control on the machine it has been done via Labview Software on a PC, FPGA and Feed Overide of the machine.

6.9 Drilling of Super Alloys

As mentioned, in a second phase the methodology developed for the Milling of Super Alloys has been extended to drilling operation.
A dedicated experimental set-up has been prepared in Mondragon for drilling operation.

The sensors configuration for drilling was composed by: Temperature Measurement System Actarus with thermocouple incorporated on the drills, and a 3-component-Dynamometer Kistler 9255B mounted on the workpiece fixturing system.

During the preliminary experimental activity it has been found that the cutting speed Vc is the most relevant input variable for the control of cutting temperature, see next picture:

For this reason in a preliminary phase it has been considered the possibility to modify both cutting speed, keeping constant feed rate, but then it has been verified that industries would accept easier the adaptation of feed rate than cutting speed. Therefore feed rate fn has been finally selected as the parameter to be adapted for keeping controlled the temperature.

An extensive experimental campaign it has been carried out in Mondragon for the correlation of the workpiece surface defects to the cutting conditions (parameters, cooling conditions and temperatures).

During the real conditions drilling tests, many accident occurred to thermocouples implemented by Actarus on the drills, therefore a special effort has been provided by Actarus and Mondragon to individuate and solve technical problems and provide a new generation of tools for drilling test bench:

Development of adaptive control for production machine

Main aim of the Adaptive Control model developed by MGEP is to keep temperature constant in drilling process by actuating on drilling parameters.

The Adaptive Control System keeps the temperature value constant by modifying the feed rate.
A subroutine is added to the main PLC program and a C program is loaded together with the PLC program for the following tasks:
- The subroutine gets (every SCAN cycle) the value of the temperature from the analog input module and sends this value to the C program.
- The C program executes all the operations (PI controller) and specifies the new value of the feed rate. This value is sent back to the subroutine.
- The subroutine modifies the value of the feed rate.
- This cycle is repeated every SCAN cycle (4 millisecons).

The maximum and minimum feed rate must be programmed depending on the tool specification.

The AC system it has been validated in real conditions, the conclusion is that the developed technology is successful in the detection of critical cutting conditions, moreover the self adaptation of feed rate work properly. On the other hand the reduction of the only drilling feed rate doesn't seem to be enough for reducing the temperature in the cutting zone. In fact it has been found that although the feed rate is reduced, there is still heat coming to the tool (and to the workpiece) and thus the only solution (coolant flow?) to avoid material damage is to stop the process. After the end of the Project the research on this topic will continue, considering the possibility to modify also cutting rate, the opportunity apply different temperature measurement systems, investigating the heat flows in cutting behavior during adaptation and considering the adaptation of drill cooling system.

6.10 Milling of Carbon Fibre

The milling and drilling of CFRP within the ADACOM project focuses on two aspects, namely the edge trimming of light weight CFRP products, including drilling and plunge milling; and the end milling of composite moulds which can radically reduce the time for developing new parts.

Initial investigations focused on the barriers to the respective processes, namely deflection of the part during edge trimming, tool wear, and high temperatures. A dedicate test rig with special purpose vacuum chuck has been developed by LOLA and tested in TCD. Applied investigations were carried out in LOLA in the first two years of the project, and then in TEKS and in TCD. Investigations in the earlier periods focused on the measurement of temperatures and forces during the machining of CFRP samples provided by LOLA with industry parameters. This work was tightly coupled with WP3 in particular the focus on the rotating temperature measurement solution provided by Actarus. The rotating temperature sensing device is unique in the market place and development work was undertaken with particular focus on composite machining within ADACOM. The ADACOM system mode developed for the composite machining case is shown below, particularly for the case of temperature measurement and varied for the case where vibration sensors were used when chatter detection was the focus of investigations, i.e. in the pioneering work carried out by TEKS.

The sample ADACOM adaption mode shown above is focused on temperature with the novel solution by the partner Actarus developed in WP3. The novel sensor required significant characterisation work which required fundamental analysis of heat flows.

This technical work is based on temperature ranges of concern in machining composites e.g. up to 200 degrees C approx. In order to develop a characteristic of the device, detailed investigation took place on quantifying the sensor characteristics in a more scientifically rigorous manner. An experimental investigation was designed in order to have a high intensity heat source from a Laser as the point source of heat on the tools.

It can be seen that the rig allows for the tool to rotate and allows the focus of the laser to be adjusted through positioning in the Z axes, the laser spot position on the tool can be manipulated axially using the laser machine tool axes.

The experimental set-up was commissioned in the last period and investigations and analysis of the results show good agreement with analytical models and FE models of the heat flow through the tool developed in ADACOM. From this basis a software concept was developed to consider model based compensation for surface temperatures based on the ITT performance. This has high potential for application in the field. The issue of chatter during milling was examined in detail by TEKS using the ADACOM approach and ADACOM control mode of parameter adaption with continuous plant identification.

The research undertaken is one of the first studies on the chatter issue during composite machining. Additional investigations undertaken between TCD, TEKS and LOLA focused on the measurement of energy during composite machining which supported the detailed work by DIAD and TEKS on life cycle analysis.

The case of milling of composites was important within ADACOM due the prevalence of composite applications currently and in the future, and the requirement for ADACOM to develop a generic standardised solution for most machining applications. The high end applications introduced by LOLA were valuable cases for the consortium to consider, in particular, these applications challenged the partners TCD and TEKS with novel set-up and lead to significant contributions to the field of applied research and direct application by TEKS and LOLA. The detailed temperature investigations have been reported at International conferences and the insight into chatter mechanisms in composite is also a unique contribution lead by TEKS. Therefore despite the unfortunate circumstances of the LOLA Company in the latter stages of the ADACOM project, the ADACOM investigations into milling of composites can be considered to be very successful through the additional work of WZL, TCD and TEKS.

Potential Impact:

Socio Economic Impact

The Life Cycle Assessment methodology has been applied to the Case Studies in order to compare the environmental impact of the state of the art industrial metal cutting processes with the impact of the processes improved through the application of ADACOM Adaptive Control. The first step carried out has been the LCA of Case Studies before ADACOM (task 2.2), then the LCA with ADACOM (task 2.2) and finally the comparison of the two conditions (task 5.4). A crucial point was the definition of the ADACOM LCA boundaries. Typically from raw materials in the earth to final disposal of waste materials back into the earth. In ADACOM Project the area of study has been restricted to the production phase: the Adaptive Control will not impact (on first approximation) on the product and its functionalities, but only on its production phase. This means to pass from a LCA approach "from cradle to grave" to a simplified approach "from cradle to gate" (the exit of from the factory), in general defined as an "Eco-profile". Two different LCA software have been applied, Simapro (PE International and Ecoinvent) and GABI, in consideration of their different databases, customized respectively by DIAD and TEKS. All the case studies have been analyzed except the Daimler ones, where it wasn't possible any comparison with the state of the art: in these cases the ADACOM System is adopted for a new application and it is not possible any environmental or energy assessment respect current solutions.

A Life Cycle Inventory has been produced for each case converting the all the inputs/outputs indicated by the LCA responsible in quantities of substances. Then in the Impact Assessment phase, the quantities of substances from the Inventory phase have been associated to environmental burdens using the CML 2001 (baseline) method, conform to ISO 14042.

Main environmental impacts categories, according to ISO 14042 are:
- Depletion of abiotic resources – This impact category indicator is related to extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation.
- Climate change – The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for development of characterisation factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide equivalent/kg emission.
- Stratospheric Ozone depletion – The characterisation model is developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/ kg emission).
- Human toxicity – Characterisation factors, expressed as Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emissions.

In order to calculate the cumulative impact of all the substances on each single impact category, it has been carried out a Characterisation, where the substances that contribute to an impact category are multiplied with a characterization factor that expresses the relative contribution of the substance. As such it can be seen as an equivalence factor. Then it has been done a Normalization of the different impact data to create a uniform unit for all impact categories and to show the relative contribution of all impact categories to the environmental problems in a region. The calculated environmental impact of the work piece material and embedded energy was very high, therefore it had been considered the impact assessment without the work piece contribution to highlight the contribution of the process on the environment. In the cases analyzed the environmental impact of processes waste treatment wasn't negligible: it was important a proper elaboration of the waste composition and disposal/recycling scenario. The typical wastes of metal cutting processes are the mixture of chips and oil emulsion (or net oil), the emulsion (or net oil) from periodic substitution of cutting lubricant on the machine tool(s) tank, the worn cutting tools. In term of waste treatment it has considered a centrifugation of the mixture of chips and oil emulsion (or net oil), to separate metal from cutting fluid. The metal chips can be sold to foundries as a by-product of the process. The emulsion obtained from the centrifugation, as also the emulsion from the periodic substitution, must be treated using chemical additives to extract oil from emulsion. The water obtained can be recycled or reintroduced on the environment, whereas the concentrated oil can be burn at the incinerator producing energy and/or heat. In case of grinding, the metal-oil slurry requires more care in the separation metal powders-cutting fluid, but the waste treatment considered was similar.

The energy absorbed by the processes it has been elaborated in the Impact Assessment adopting an European energy mix that consider the average value of the shares of various energy sources on 27 EU Countries. This assumption is important in order to obtain from the LCA environmental impact data that are significant at European scale and not only at National level. In next table is indicated the share of energy sources for the single European countries and the EU27 mix.

Shares of various energy sources in total gross energy consumption by fuel in 2009

The ADACOM System itself has a power consumption, that has been considered comparable to a Laptop consumption (39W).

The environmental evaluation of Project results has been very positive: all the case studies showed an environmental impact reduction respect to the state of the art, when ADACOM System is applied. It is clear that in some cases, like e.g. Heidelberg cylinder grinding, the main benefits are economic, never less also in that cases an environmental impact reduction has been calculated. At the opposite the CRF case study represents a particular situation, where the ADACOM "assistance" take to very high environmental improvements.

Regarding the energy consumption evaluation, the ADACOM System application resulted beneficial for all the case studies (see next diagram).

At this purpose it is important to outline that the energy save is a key aspect for industries, because it take, at one time, reduction of production costs and environmental impacts, that are beneficial for the competitiveness and market image of the companies. Other crucial advantages of the energy save are related the high variability of energy costs. When the manufacturing industries define new production plants they consider a minimum period of usage of 10 years (sometime more), but they don't not know at that time the evolution of the energy costs during next 10 years. The reduction of power consumption represents the opportunity for the industries to reduce the economical impact of this uncertainty.

From the Social point of view, it is important to consider the relevance of ADACOM energy saves on European companies' competitiveness and consequent preservation of employment. Considering the typical production plants, the energy cost has a major impact for EU industries than for their competitors in emerging countries: all kinds of production energy saves increase the competitiveness and preserve the occupation in EU.

The LCA has been applied also to provide a quantification of the social benefit of ADACOM System application on the human health, the ecosystem quality and the save of resources save, using the LCA Eco-indicator 99 method.

The Eco-indicator 99 defines three types of damage categories:
- Human Health (unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted). This category includes the number and duration of diseases, and life years lost due to premature death from environmental causes. The effects included are: climate change, ozone layer depletion, carcinogenic effects, respiratory effects (organics and inorganics) and ionising (nuclear) radiation.

- Ecosystem Quality (unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species). This category includes the effect on species diversity, especially for vascular plants and lower organisms. The effects included are: ecotoxicity, acidification, eutrophication and land use.
- Resources (unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade). This category includes the surplus energy needed in future to extract lower quality mineral and fossil resources.

The application od ADACOM System results in a decrease of processes impacts on Human Health, Ecosystem Quality and Resources (consumption). Also in case of social impacts it can be observed that all the case studies show relevant advantages when ADACOM System is applied. The data obtained are summarized in next diagrams.

Dissimination

Publications
- An Integrated Telemetric Thermocouple Sensor for Process Monitoring of CFRP Milling Operations, K. Kerrigana, J. Thil, R. Hewison, G.E. O'Donnell, Proedia CIRP 1 2012, 449-454.
- Machine tool process monitoring and machine condition monitoring – examining data acquisition gateways for process adaption, J. Morgan, G. Eisenblätter, J. Trostel, G.E. O'Donnell International Manufacturing, Conference, 29, 2012 1-10.
- Control adaptativo del proceso de taladrado, Pedro J.Arrazola, Congreso de MH y Tecnologías de Fabricacion Proceedings of XIX (2013) / every 2 years Invema Donostia-San Sebastián, 2013 .
- Monitorizacion del proceso de mecanizado Pedro J.Arrazola Seminar: Tecnological seminar on Cutting, Proceedings of Seminar, Invema, Elgoibar, 2011.

Exploitatable Results

1. Adaptive Control hardware platform

Innovation content of result:
-First time implementation of different adaptive production Strategies to machining processes represented by eight industrial case studies
-Online adaption modes for industrial production
Who will be the customer?
-Manufacturing industry in almost every sector as automotive, aeronautics, printing machines, etc.
-Machine tool manufacturers.
-Sensor and process monitoring solution providers

What benefit will it bring to the customers?
-Increase of robustness, flexibility, performance and re-configurability.
-Automatically identification and stabilisation of critical parameter of the machine tool
-Reduced energy input to process, e.g. finding optimal energy input early in process
-Reduced waste parts by getting first part right
-Productivity improvement, optimal part throughput
-Reduced operator workload by using machine intelligence
-Achievement of an online quality control system for mass customization and small batch production

2. System architecture for adaptive control of metal cutting
Innovation content of result:
-system architecture on how to implement adaptive control systems to machining processes
Who will be the customer?
-Manufacturing industry in almost every sector as automotive, aeronautics, printing machines, etc.
-Machine tool manufacturers.
-Sensor and process monitoring solution providers

What benefit will it bring to the customers?
-Increase of robustness, flexibility, performance and re-configurability.
-Automatically identification and stabilisation of critical parameter of the machine tool
-Reduced energy input to process, e.g. finding optimal energy input early in process
-Reduced waste parts by getting first part right
-Productivity improvement, optimal part throughput
-Reduced operator workload by using machine intelligence
-Achievement of an online quality control system for mass customization and small batch production

3. Process adaptive control strategies
Innovation content of result:
-Strategies how to implement adaptive control systems to machining processes
Who will be the customer?
-End users in most manufacturing sectors such as automotive, aeronautics, printing machines, etc.
-2. Machine tool manufacturers.

What benefit will it bring to the customers?

-Increase of robustness, flexibility, performance and re-configurability through automatically identification and stabilisation of critical parameter of the machine tool
-Reduced scrapped parts by getting first part right
-Productivity improvement, optimal part throughput
-Reduced operator workload/variability by using machine intelligence
-Achievement of an online quality control system for mass customization and small batch production

4. Adaptive Control hardware platform: a. Open loop adaptive platform for CFRP machining (lola case study)
Innovation content of result:
-The high quality of the waterjet surface will allow for the part to be produced to the final dimensions with very little finishing required
Who will be the customer?
-Wheelchair and other medical device manufacturers
What benefit will it bring to the customers?
-Faster process times, higher margin

5. Energy saving strategies
Innovation content of result:
-Companies with a high energy bill might want to optimize their operations for energy efficiency rather than maximum throughput. Energy efficiency is highly topical for all manufacturing in Europe currently
Who will be the customer?
-Mass producingsubcontract machinist
What benefit will it bring to the customers?
-During periods of high energy cost at peak times the machines can be optimized for high energy efficiency whereas during periods of low cost ie during night time hours the machines can be optimized for high throughput

6. Human Machine Interface for machine tool process and condition monitoring
Innovation content of result:
Companies In today's production, Heidelberg has to face reworking and rejection costs due to "chattering marks" on the cylinder surface. It is a highly sensitive process, which can result in significant downtime in order to establish the cause of the error. One focus is the process comparison and documentation of a stable process to a process with scattering marks to evaluate specific error charts. The aim is the reduction of off-times of the machine due to quantification of critical influence parameter of machine tool components. A modular Compact RIO System (based on hardware from National Instruments) has been developed and commissioned and has been installed in the grinding machine in order to record and to analyze data from accelerometers and axes position sensors in a standardized manner.

Who will be the customer?
Clients that require detailed process and condition monitoring of high end machine tools on high value components. E.g. Grinding of medical components, machining of large components such as gears for wind turbines.

What benefit will it bring to the customers?
A reduction of off-times of machines due to quantification of critical influence parameter of machine tool components.

7. New design sensors implemented on machine tool

Innovation content of result:

New kind of insert have been created, included sensor, and new tool attachment have been transformed to obtain the result with specific system of wireless data transmission.

Who will be the customer?

Everyone who mills or turns material with high precision and/or who wants to improve tool cycle life or decrease time to set production parameters

What benefit will it bring to the customers?

Less tool consumption, better quality of machining, less waste. Better control of cutting condition

List of Websites:

http://www.adacom.eu.com/