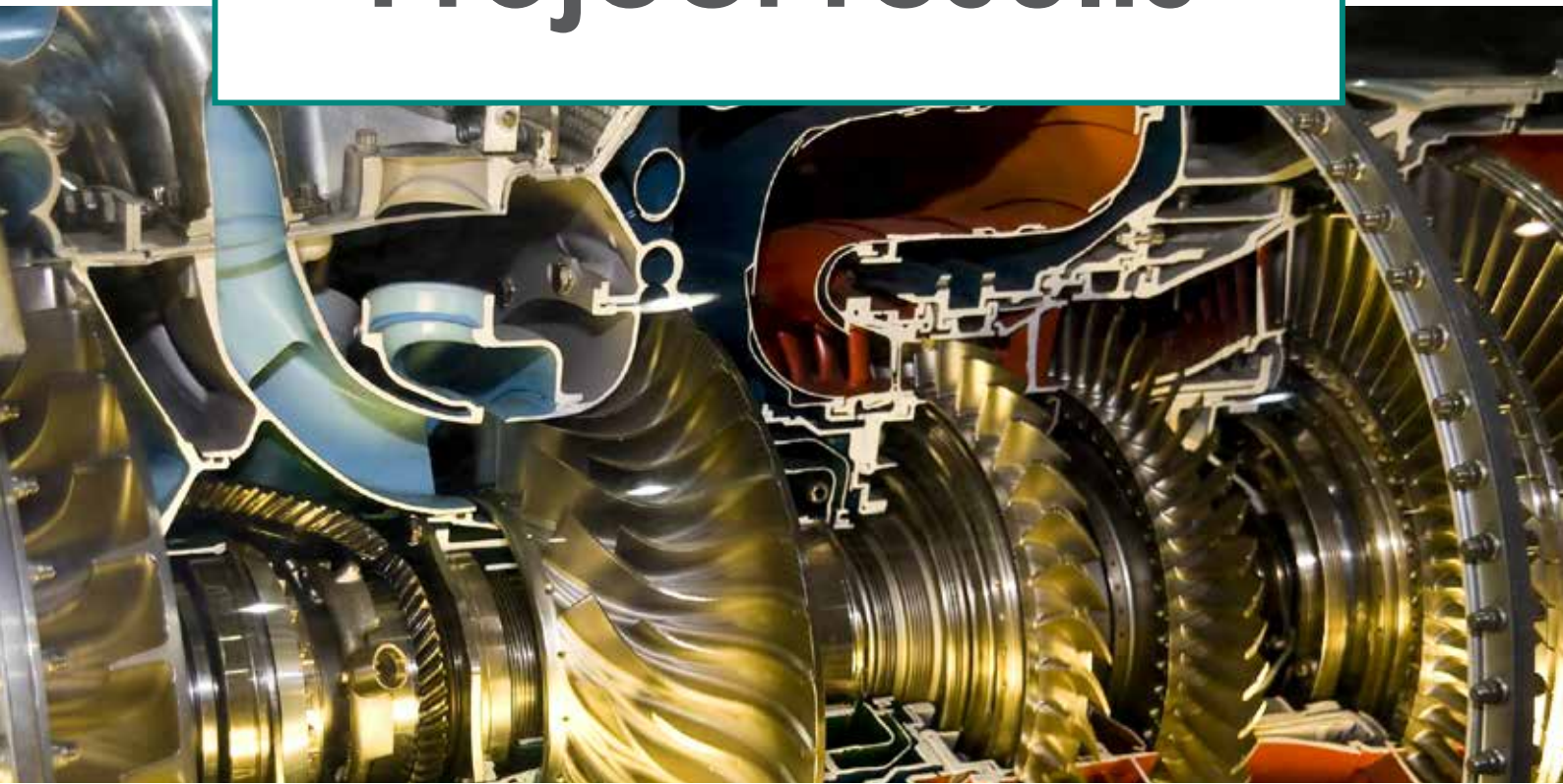




Intelligent fixtures for the machining of low rigidity components

# Project results



This project has received funding from the European Union's Seventh Framework Programme under grant agreement no 609306

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## INTEFIX – Intelligent Fixtures for the machining of low rigidity components

The INTEFIX project aims to increase the performance of the machining processes by the use of intelligent fixture systems, allowing the monitoring, control and adaptation of the process to obtain suitable results according to precision, quality and cost requirements.

Typically, the main functions of fixtures are to securely hold and accurately locate the workpiece considered as a non-deformable body. Nowadays, the high precision required and the need of increasing the performance of the manufacturing process drive to other important functions of the fixtures taking into account aspects like the deformations, vibrations and distortions in the workpiece during processing. The project uses adaptive fixtures to control and adapt the behavior of the machining system in order to obtain suitable results in manufacturing precision, quality and cost.

Moreover, INTEFIX deals with the integration of new and state-of-the-art technologies (sensors, actuators, control algorithms, simulation tools...) applied to the workpiece handling systems to develop intelligent and modular fixtures capable to modify the behaviour and interactions between the process and systems in machining operations; reducing time and costs with improved performance and capabilities.

The experiments are divided into three scenarios oriented to obtain a solution to different problems associated to machining process:

- **SCENARIO 1: VIBRATION.** Workpieces with problems of vibrations during machining. The intelligent fixture counteracts vibration problems by changing the dynamic properties, stiffness, damping, etc.
- **SCENARIO 2: DEFORMATION.** Workpieces with problems of deflections/ distortions during machining. The intelligent fixture counteracts the displacement of the workpiece through process development forces.
- **SCENARIO 3: POSITIONING.** Workpieces with problems of reference setting. The intelligent fixture introduces small movements to correct linear and angular alignment of the workpiece.

The developed solutions are validated in 11 real test cases from the aeronautic, railway, automotive and machine tool sectors.

### Project fact sheet

Duration: 2013-2016

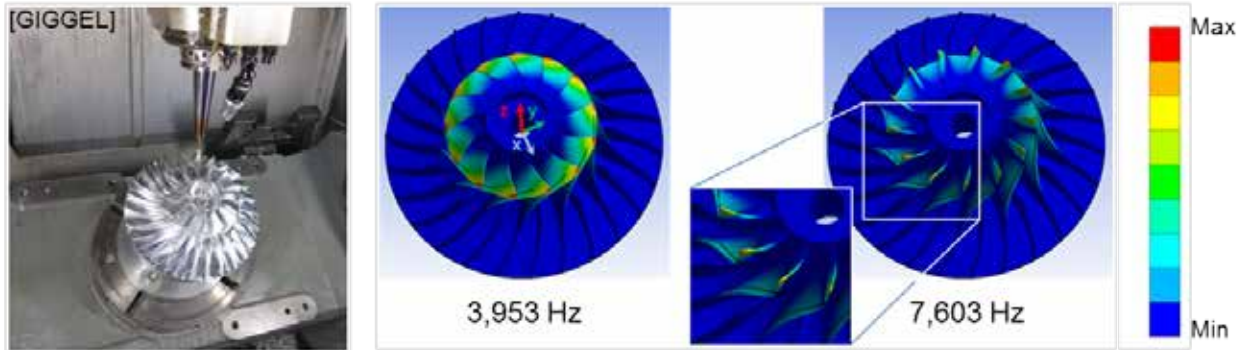
Budget: €10.253.513

EC contribution: €7.499.998

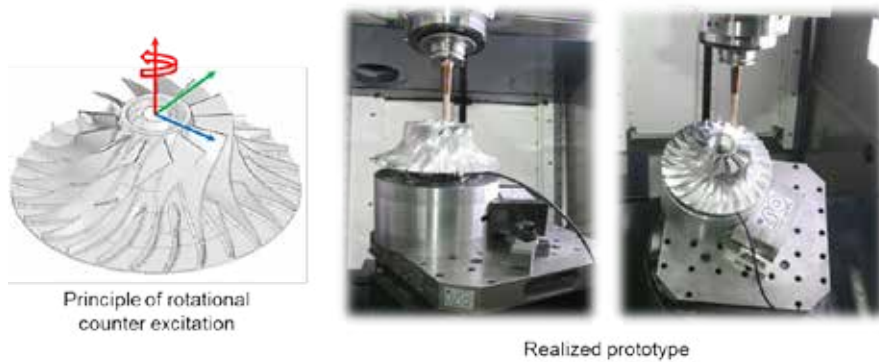
32 partners:

- SMEs: 19
- Industrial organizations: 6
- Research and academy: 7

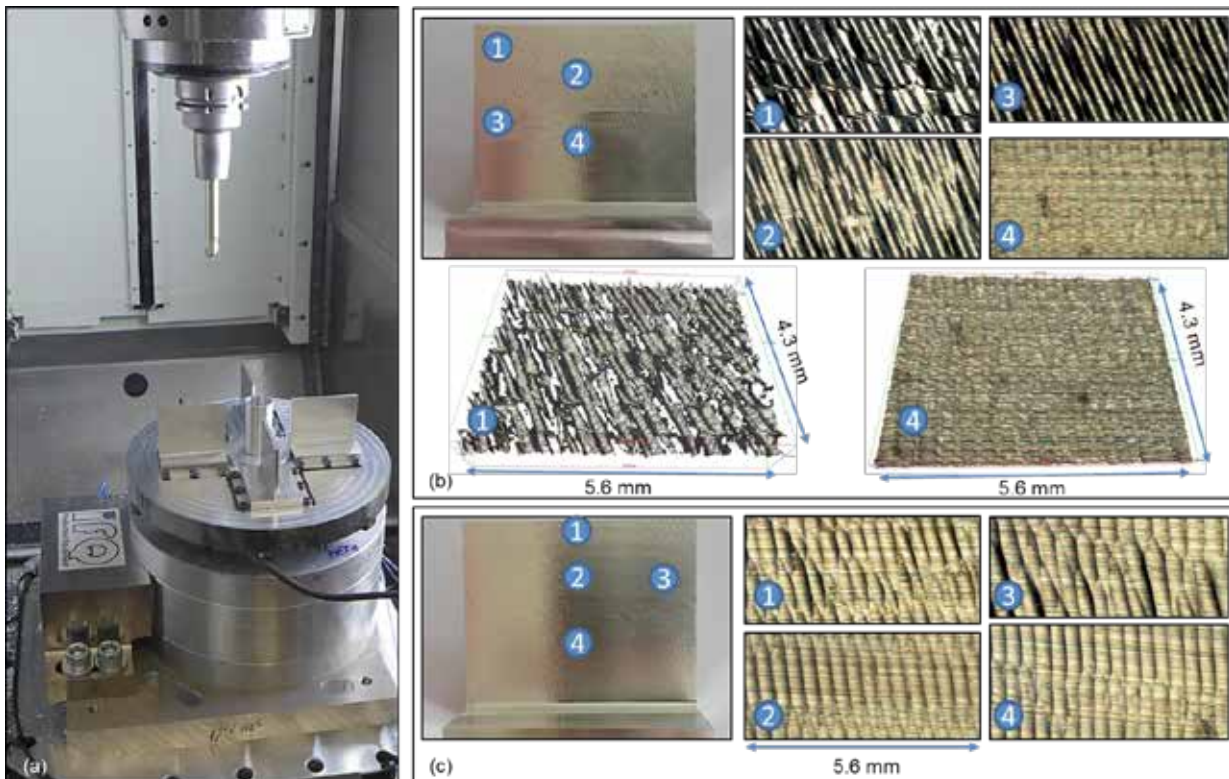




Workpiece vibrations during milling of thin walled impeller blades



Principle of rotational counter excitation and realized prototype of intelligent fixture



Intelligent fixture prototype in machining test setup (a) and achieved processing results without (b) and with (c) counter excitation

## Case study 1.1: Identification and active damping of critical workpiece vibrations in milling of thin walled impellers/blisks

### Main technical issue

In milling of impellers and blisks, critical workpiece vibrations of thin-walled blade structures occur due to the excitation by the process forces and the dynamic compliance of the sensitive elements of the parts. Workpiece vibrations lead to an unacceptable waviness and chatter marks on the blade surfaces and thus to the production of defective parts. Also, these vibrations provoke an increased tool wear progress. The machining processes are characterized by the use of long and slender milling tools which allow machining of the blade surfaces and the geometries between the blades. Typically, tool rotational speeds above 10,000 min<sup>-1</sup> and tools with 3 (and more) cutting edges are applied. Process vibrations occur at both the tool and the workpiece side. The impeller regarded here has a diameter of 200 mm and a height of 65 mm. The workpiece material is Al7075. The weight of the workpiece amounts to approx. 3.5 kg. The dynamic behavior of the impeller blades can be characterized by the natural frequencies of the bending modes. A first natural frequency was identified at 3.9 kHz by FE analysis. During the milling processes, the dynamic response of the blades changes continuously because of the moving contact point between the tool and workpiece and the change of the modal parameters due to the material removal.

### Proposed technical solution

The first objective of the newly developed intelligent fixture is to allow the detection of critical process vibrations during the milling process by integrated sensor systems. The second objective concerns the mitigation of regenerative chatter vibrations. This is realized by the introduction of counter excitations of the workpiece by the fixture, which disturb the regenerative effect. In order to implement counter excitations of the impeller during milling processes, an intelligent rotational chuck was developed. The approach of rotational counter excitation exploits the fact that a rotational vibration of the workpiece provokes bending vibrations of the blades.

A light weight CFRP element with integrated piezo patch transducers is mounted at the inner rotating core of the actuated structure which carries a clamping mandrel in order to fixate the workpiece. The CFRP provides 'sensory arms' which are pre-stressed against the bottom surface of the workpiece during clamping. By this pre-stress, the contact of the sensory element with the workpiece can be guaranteed and the sensor sensitivity is improved. Several sensory test structures (provided by INVENT) were analyzed in experiments.

### Main advantages of the solution

The rotational chuck was proven in milling tests (tool diameter: 12 mm, tool rotational speed: 10,600 min<sup>-1</sup>, z = 2, ae = 1 mm, ap = 0.6 mm, vf = 3,710 mm/min) without and with counter excitations (fex = 350 Hz) using straight test workpieces. The resulting workpiece surfaces were measured by an ALICONA InfiniteFocus device. A smoother and more regular surface can be achieved applying the counter excitation

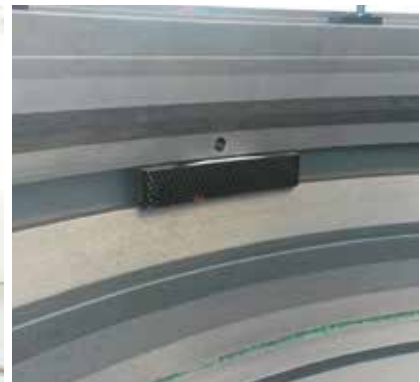
Main advantages of the solution are:

- Detection of critical process vibrations during milling of thin walled workpiece elements;
- Mitigation of regenerative chatter effects by introduction of active counter excitation;
- Reduction of defective parts production.

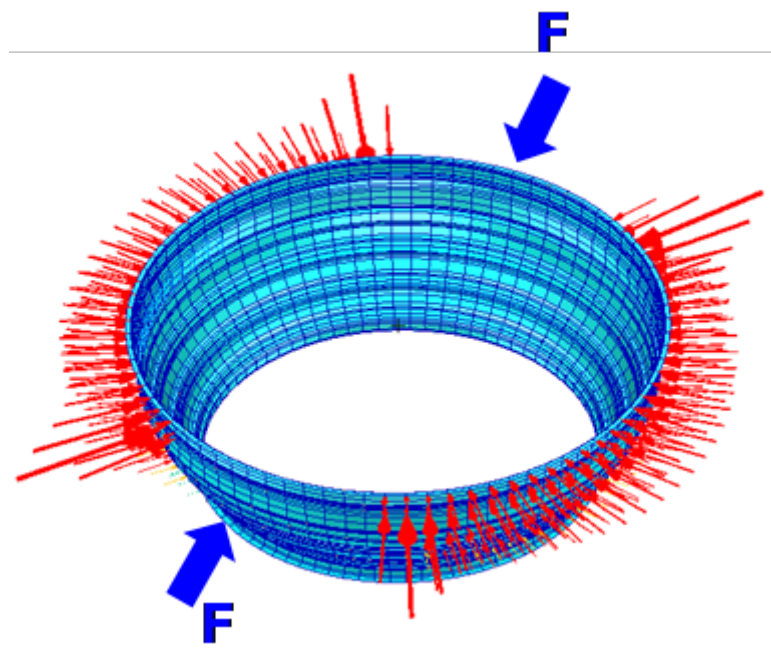




Workpiece under assessment and location in the turbine



Actuation assembly



Simulation of the improvement of contact stiffness with applied loads for controlled deformation



## Case study 1.2: Turning of low pressure turbine casing

### Main technical issue

The objective is the improvement of the turning performance of a turbine case made of low machinability Inconel 718 alloy with 1800 mm in diameter, 550 mm in height and common thickness of 2.5-6 mm. The performance of the machining process is limited by the presence of vibrations and deformations that lead to limited cutting conditions and reduce the tool lifespan, affecting also the quality of the workpiece.

The work performed has allowed the identification of the main limitations of the current fixture and the manufacturing process. The key point is related to the contact between the workpiece and the fixture: due to the size and flexibility of the workpiece and to the fact that the contact cannot be sustained all around the workpiece, the process forces drive to discontinuities in the contact of both elements. Another point is the lack of apparent stiffness of the workpiece that finally results in vibrations and deformations during processing.

Up to now, the solutions tested have consisted of the incorporation of flexible elements to improve the contact stiffness of the workpiece.

### Proposed technical solution

The current fixture has been modified adding several elements able to change and adapt the behaviour of the workpiece. This modification includes the integration of sensors, actuators and advanced materials.

The improvement of the workpiece behaviour has been tackled using three approaches:

**1 - Active modification of mechanical impedance:** This solution deals with the use of active vibration reducers. The proposed system create a counteracting inertial force with a magnetic actuator controlled in closed loop, minimizing the vibrations measured by the integrated accelerometer inside the system. The effect on the workpiece is a reduction of the dynamic amplification factor in a wide frequency bandwidth.

**2 - Controlled deformation:** This solution deals with the use of four actuators integrated in the fixture to apply controlled forces in defined areas of the workpiece. The objective is the control of the deformation of the workpiece applying forces that increase the stiffness in the area near the cutting tool, avoiding shocks and vibrations. The local contact between the workpiece and fixture is improved and the apparent stiffness of the workpiece is increased. Thus, the workpiece is being clamped by an active system under a controlled hyperstatic clamping situation.

**3 - Use of CFRP for locators:** This solution deals with the introduction of passive CFRP elements to substitute the metallic rings used as locators in the current fixture. The use of CFRP increases the damping (10 times higher than steel) of the fixture without reducing the stiffness. In this way, the effect of the shocks can be minimized.

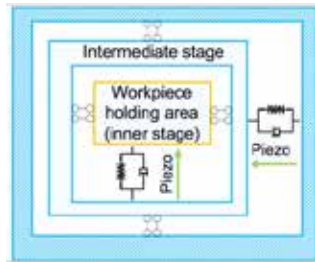
### Main advantages of the solution

The developed intelligent fixture allows the improvement of the workpiece behaviour and the cutting conditions can also be increased obtained a better machining process performance.

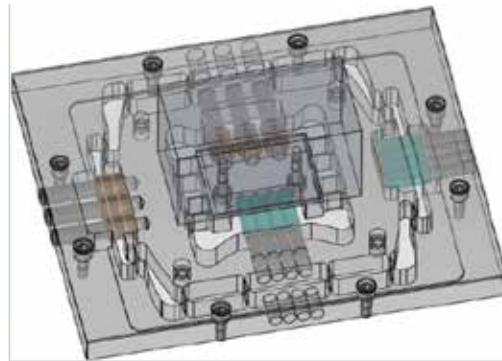
This solution is mainly oriented to large components with different behaviours depending on the zone of the workpiece or components that change their shape during processing, requiring the modification of the fixture configuration to adapt the clamping of the workpiece during the process.

This is applicable to many different components that must be analyzed before proposing a fixture configuration using the proposed systems and approach.

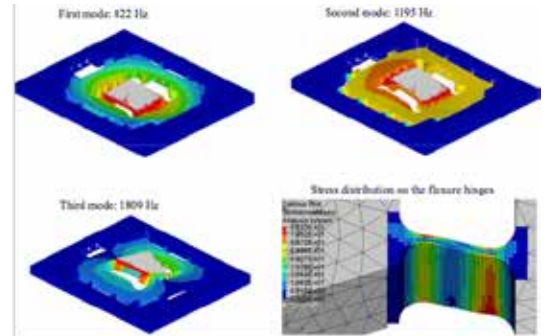




**Concept**

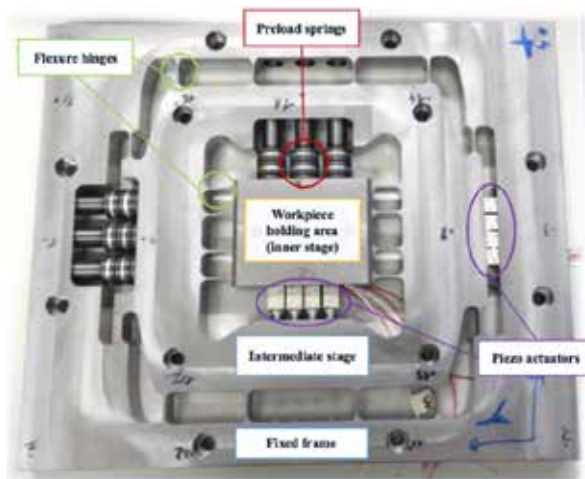


**Design**

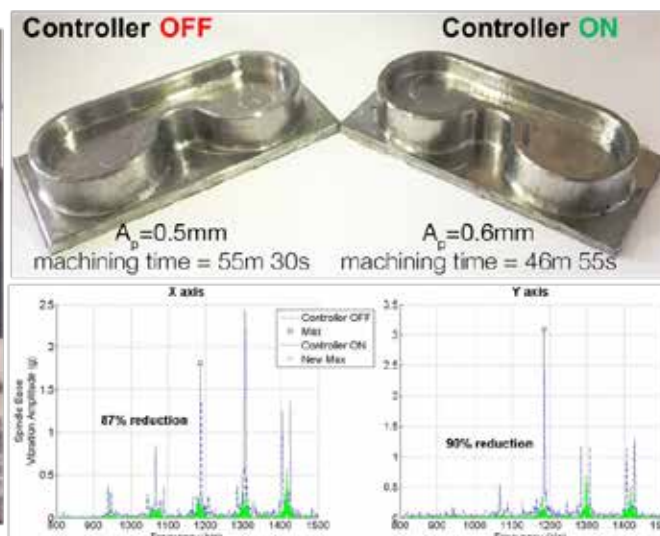


**Validation**

### Design of the intelligent active fixture for chatter mitigation



**Manufacturing and assembly of the active fixture prototype equipped with sensors and actuators**



**Chatter vibration mitigation and increased productivity results on industrial test-case**



## Case study 1.3: Auto-adaptive vibrations and instabilities suppression in general milling operations.

### Main technical issue

Auto regenerative vibrations, known also as chatter, constitute a limit for the milling process productivity since they reduce the allowable material removal rate. In order to lower the levels of vibration, the manufacturing engineers are compelled to decrease the depth of cut of the machining cycle or use bulkier tools that limit the accessibility to some features of the workpiece. This is an important issue in many industrial sectors, like the die manufacturing one, that is characterized by very long machining time due to the complexity of the workpiece and the required surface finish. A system that could reduce the occurrence of chatter without the modification of the machining set-up (chosen tooling) would increase the process productivity without creating new constraints to the production.

### Proposed technical solution

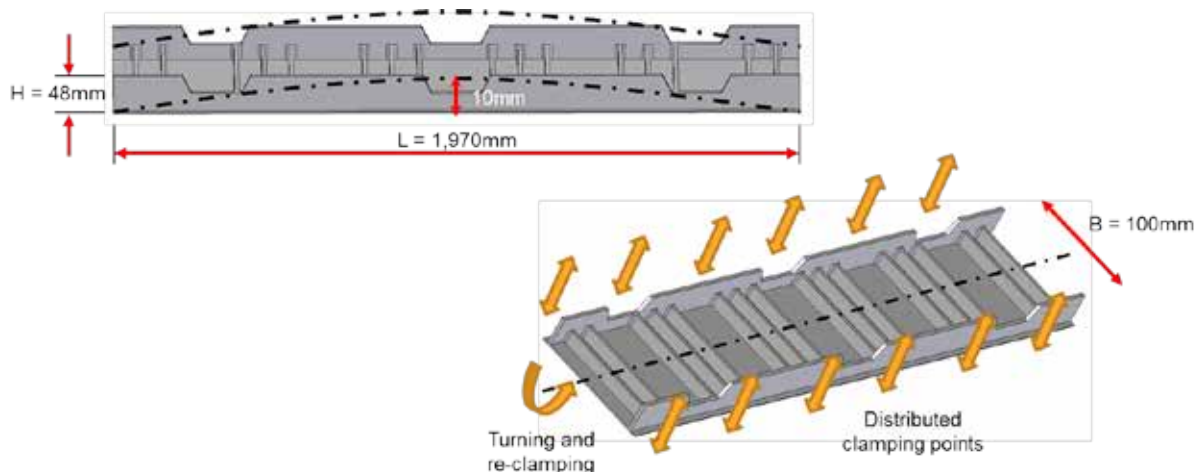
The developed solution is based on an in-depth study of the regenerative nature of chatter. The system has been created with the objective to “break” the regenerative effect of the chatter vibrations. This result has been obtained thanks to the introduction of an actuation of the workpiece in order to reduce the regeneration of a vibrated surface at each pass of the tool tooth. In order to be as not intrusive as possible, the actuation of the system using piezo has been integrated in a new design fixture. The advantage of this solution is that the manufacturer could fix the workpiece using its usual approach, avoiding to reduce the accessibility of the features and surfaces that must be machined. The developed fixture integrates not only the actuation but also some accelerometers, used to monitor the status of the process and control the actuation in order to have a positive result. Thanks to these sensors, it has been possible to create an autonomous system that starts the operation of the actuators only when the chatter arises and control the actuation using the information about phase and amplitude of the workpiece vibration. The control logic is autonomous and could reduce the vibration level of chatter for a large variety of process parameters, toolpath and tooling. It is not necessary to create a model of the tooling and process like in other chatter avoidance approaches; this is a very positive issue for the application in a manufacturing plant. The control logic is installed on an external PLC that process real-time the sensors output and decide whether and how activate the actuators.

### Main advantages of the solution

The main advantage of the developed active fixture is to increase the process productivity maintaining the same quality of the surface finish, without creating new constraints that could limit the accessibility to the workpiece. The solution is easily acceptable, since it has a very low profile, 5 cm with adaptor plate, and could be installed on nearly all the actual milling machines. The advantage of the autonomous control logic is that no advanced knowledge is required to the operator to use the active fixture, he just needs to turn the system on after installing it properly. A brief recap of the obtained advantages measured in Girardini, a company that operates in the die manufacturing sector, are:

- Decrease the roughing operations by more than 10% of the productivity time, that leads up to €15k savings for a medium sized die;
- Operate the machine without human presence and better use of the resources improves the OEE factor of +5% generating up to €18k savings for a medium sized die;
- Extended machinability of the workpiece by the use of slender tool machining;
- Equipment working safely during plant closure;
- Increase competitiveness due to the introduction of innovative solutions.





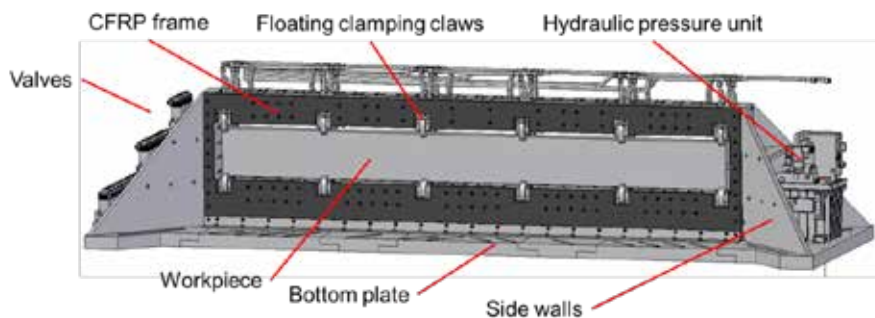
**Workpiece distortions due to residual stresses in milling and current clamping, turning and re-clamping at distributed clamping points**



**'PosiFlex' floating clamp**  
(2x 6 mm; 7 kN at 250 bar)

**Floating clamping claw**  
(8 mm / 10 mm; 7,5 kN at 250 bar)

**Test fixture frames for adaptive clamping with two different types of floating clamps [by Roemheld]**



**Final intelligent fixture prototype (CAD design and application in industrial environment)**

### Case study 2.1: Detection and compensation of workpiece distortions during machining of slender and thin-walled aerospace parts

#### Main technical issue

Thin-walled workpieces are particularly affected by distortions due to residual stresses which are induced or delivered during the machining processes. In this case study, the reference workpiece is a structural aluminum part of the following dimensions: length: 1,970 mm, width: 100 mm and height: 48 mm. The final workpiece is machined out of an aluminum block by several milling steps. After the machining, removal of the clamps and demounting the workpiece off the fixture are completed, distortions occur which lead to a bended shape with a height difference of up to 10 mm between the center and the edges of the part. These distortions are not always distributed evenly over the entire length of the workpiece. In order to reduce the resulting shape deviations, several re-clamping steps are currently conducted in which the workpiece is dismounted off the conventional fixture, turned and clamped again in order to allow machining from both the front and the rear sides. The aim of this procedure is to achieve a uniform distribution of residual stresses and, thus, minimize distortions. However, this manual re-clamping is a costly and time consuming solution to overcome the given problem. Furthermore, the re-clamping not always leads to acceptable results in terms of workpiece shapes which satisfy the tolerances defined by the customers.

#### Proposed technical solution

Within the INTEFIX project, an investigated approach is based on the application of a fixture frame that integrates several adjustable clamping elements. The fixture frame holds the workpiece in an upright position, so that accessibility of the clamped part from the front and the rear side is provided. This allows automated both-sided milling operations inside a horizontal machining center with a rotary table. The adjustable clamping elements allow an adaptation of the locations of the clamping points to distorted shapes of the clamped workpiece by floating degrees of freedom (DoF). By this, a relaxation of the workpiece at intermediate states of the total machining process becomes possible. Thus, residual stresses can be compensated and the final distortions can be reduced. During the milling operations, the floating DoFs of the clamping elements are blocked by hydraulics. In order to align the locations of the clamping points actively, additional hydraulic actuators are integrated into the fixture system which move the floating clamps separately. For an adaptation of the clamping point locations to distorted intermediate workpiece shapes, a controlled positioning of the floating DoFs is necessary. To obtain measurement signals for position and force control, sensors are integrated into the actuation sub-systems. Consequently, with its sensor, actuator and control integration, the fixture provides the additional 'intelligent' functionality to adapt itself to occurring distorted part shapes.

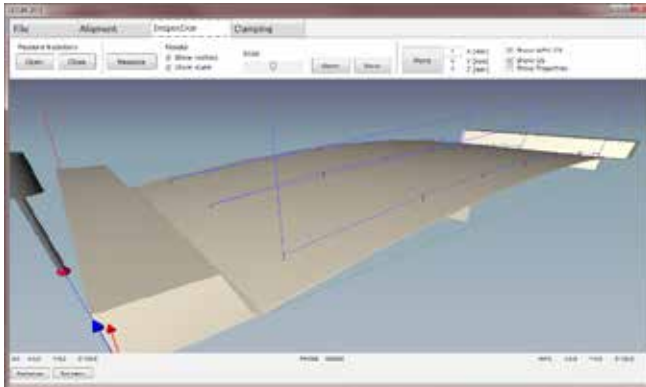
#### Main advantages of the solution

Main advantages of the solution are:

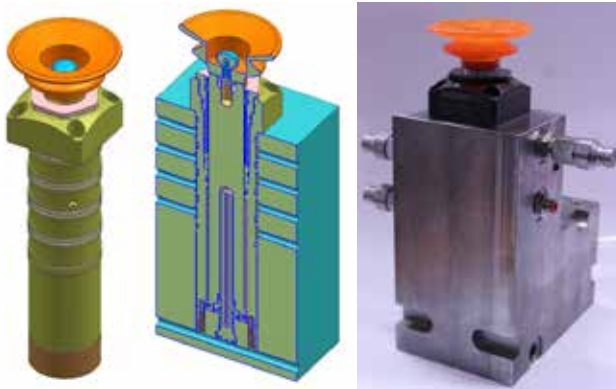
- Avoidance of re-clamping by automated both-sided machining;
- Reduction of workpiece distortions by relaxation of intermediate residual stress distributions;
- Adaptive configuration and adjustment of clamping points based on sensor and actuator integration.







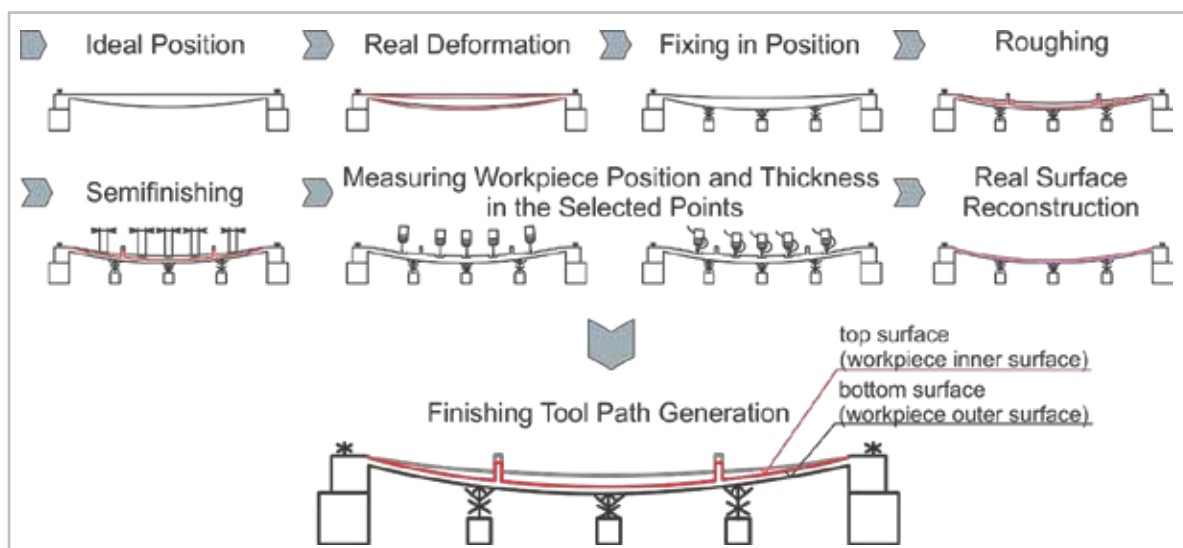
Control software for easy alignment, inspection and thickness measurement on the workpiece



New developed fixture unit



Demonstration thin-walled part machining under real conditions with adapted NC code



## Case study 2.2: Clamping of thin-walled curved workpieces

### Main technical issue

The case study is focused on production of thin-walled curved workpieces typical for structural parts of airplanes. The current issue in the workpiece clamping and subsequent machining is changeable workpiece stiffness. The existing clamping strategy and machining strategy cause large local deformation of the part. As a result, the workpiece wall thickness is out of tolerance and subsequently the part's weight was also out of tolerance. This causes part weight changes which is also undesirable.

### Proposed technical solution

**Workpiece clamping:** New fixtures with integrated support and clamping function were developed. The workpiece is clamped using a vacuum. Concurrently, suitable control for automatic position setting of the fixtures was developed. A suitable thickness measurement sensor was selected and integrated into the machine tool. The new fixture elements are autonomous and plug-and-produce ready, with integrated safety to monitor the minimal workpiece clamping force.

**Machining planning:** Suitable tools and cutting conditions for roughing and also finishing operations were selected and optimized. The main criterion for tool selection is minimization of the cutting force in the surface normal direction. The main criterion for cutting condition settings was chatter avoidance during thin wall machining. The method was developed for adaptive modification of finish tool path with respect to current workpiece thickness and deformation.

**Process automation:** The integration of thickness measurement sensors in order to control the precision of the workpiece and subsequent modification of the tool path for finishing operations; development of a unique software for quick and easy workpiece inspection and thickness measurement.

### Main advantages of the solution

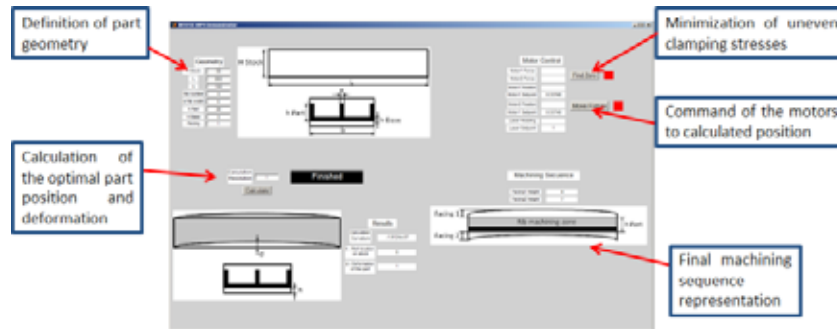
The proposed manufacturing process leads to shortening of the production time by about 15% with requested quality of  $Ra=0.8$ . The proposed manufacturing procedure is beneficial from the productivity point of view. Although the wall thickness is over the upper limit at some points, the part total weight is on the requested upper limit. It means that the requested key parameters were fulfilled using the described fixture system and manufacturing technology. The proposed manufacturing procedure is acceptable from the accuracy and weight point of view. A group of fixtures, including the necessary harness and control, offers a universal possibility how to replace a set of six specific fixtures designed as a mould with part negative shape. Moreover, the new fixtures can be used for clamping during machining of both workpiece sides. Comparing the total price of the whole existing fixture set with the proposed universal solution, it can be seen that the proposed fixture system is cost-effective. The main advantages for end-users are summarized in the table below.



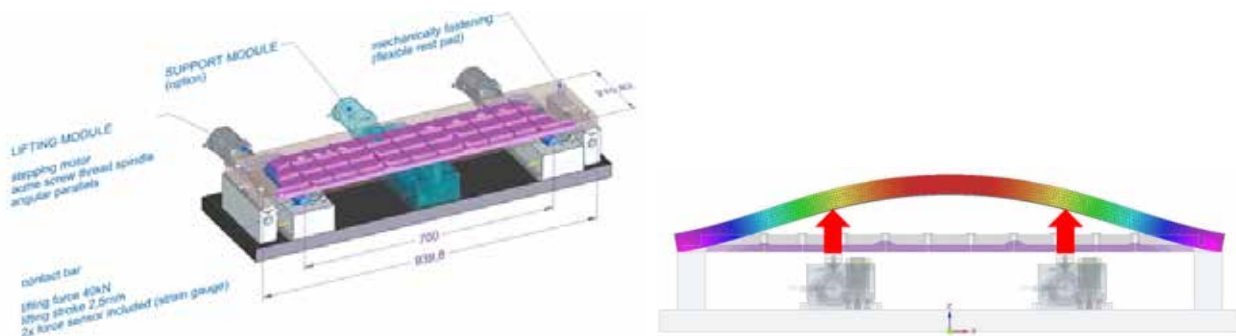
Parameter	Requirements	Existing solution	New solution
The wall thickness accuracy of the workpiece	$\pm 0.05$ mm	$\pm 0.1$ mm	$-0.05 / +0.1$ mm
Workpiece weight	max. +1 kg	up to +2 kg	+1 kg
Surface roughness	Ra 0.8	Ra 0.8	max. Ra 0.8
Machining time (of the bottom side)	to minimize (with respect to surface roughness)	100 hours	85.1 hours
Price	to minimize	€130000	€95000



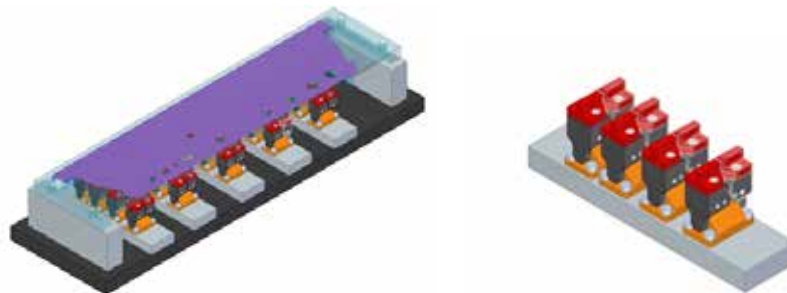
Parts manufactured with the same machining process. Notice the different distortion on both parts



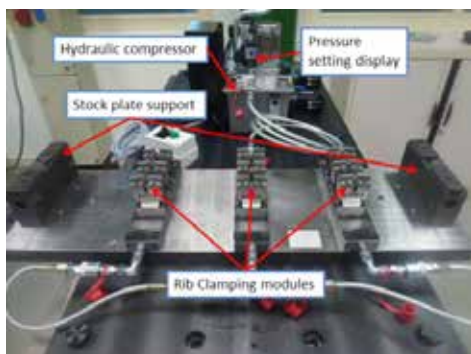
GUI for the control of the fixture and minimization of part distortion



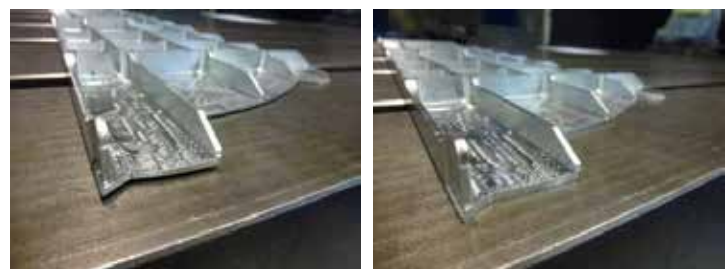
Structure and main function of the first fixture



Design for the second fixture with flexible rib clamping modules



Overview of the second step fixture



Part shape after the application of the sequential machining procedure (left) and the application of the solution presented here (right)



## Case study 2.3: Distortions in aeronautical structural parts

### Main technical issue

At present, aircraft manufacturing companies are heavily driven by weight and cost reduction initiatives. To that end, and specifically related to structural components, the use of highly slender ribbed parts made on newly developed aluminum alloys has been extensively developed over the last decade. However, due to the nature of the materials used and the asymmetrical geometries related to these slender ribbed components, the appearance of geometrical distortions after the manufacturing of these components is a major issue. Furthermore, non-repetitive residual stress fields on the stocks make the appearance of non-acceptable distortions on some parts when following the same manufacturing process. In order to overcome these distortion problems, the classic solutions have been based on the incremental removal of material from opposite sides of the machining stock, so the distortion could be balanced. While this solution could lead to a distortion-free part, it generates different inconveniences due to the difficulty to clamp the part on the already machined ribbed zone without damaging the fins, or the long machine and set-up times required to carry out the whole machining of the part.

### Proposed technical solution

The present paper presents the work carried out for the development of an easy to implement solution for the manufacturing of distortion-free parts. On the one hand, an analytical model has been developed for the calculation of both the residual stress state of the aluminum stocks and the final distortion of the parts after the machining process. On the other hand, two fixturing solutions have been developed. The first one allows modification of the initial state of the stock in case it is required for the minimization of the final distortion of the part. The control of this fixture is coupled with the analytical model for the part distortion on a simple-to-use graphic user interface, so it can be used on the shop-floor without the need of a high power computer. Based on the calculation model developed, this interface indicates the best way to machine the component, bringing down the whole manufacturing process to only two machining steps and reducing the whole machine time significantly in comparison to solutions based on sequential passes. Finally, the second fixture helps on clamping the ribbed parts without damaging the fins. It is based on hydraulic clamps which apply the clamping force in a balanced way, so the fins are not deformed nor damaged during the clamping process.

### Main advantages of the solution

The application of the present developments in comparison to the conventional machining process has:

- Improved the part accuracy from 2 mm distortion to 0.3 mm distortion thanks to the application of the distortion minimization procedure.
- Reduced machine time from 4 days to 2 days due to the avoidance of the sequential clamping procedures.

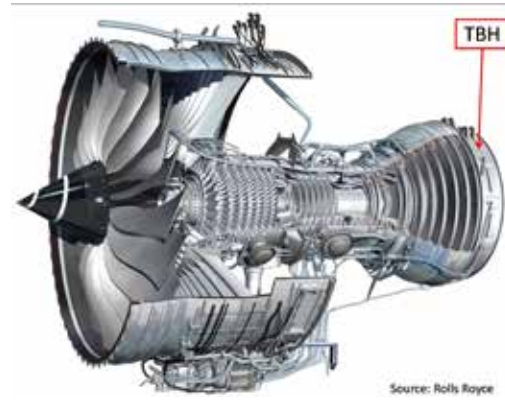
Thanks to the application of the present solution, it is possible to ensure the quality on ribbed slender structural components, avoiding the generation of defective parts and the material and energy waste associated to it. Furthermore, the machine time required for their manufacturing could be further reduced since the sequential machining is no longer needed, improving the competitiveness of the manufacturers on the market.



Parameter	Requirements	Existing solution	New solution
Final part distortion	1 mm	2 mm	0.3 mm
Machining time for the whole part	To minimize it as much as possible	4 days	2 days Further reduction possible by modifying the machining process
Price	The lowest possible	No specific solution to avoid distortions	From €2500 to €25000 depending on part's geometry

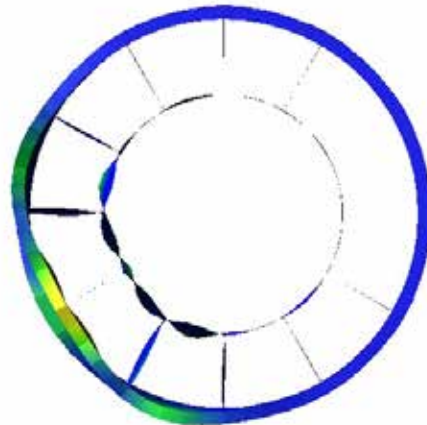
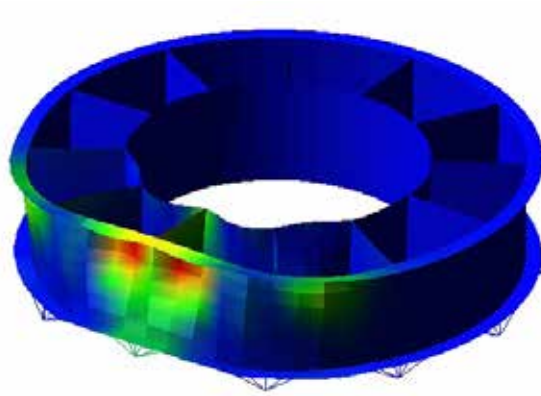


Workpiece under assessment



Source: Rolls Royce

Location of the workpiece in the turbine



Problem to solve: Simulation of the scaled distortion associated to a 0.1mm deviation in the clamping point



System mounted in the fixture for the set up process

### Case study 2.4: Machining of aircraft turbine support structures

#### Main technical issue

The main objective is the control and minimization of the deformation of large, complex geometry and low stiffness workpieces during the setup and clamping process in order to achieve improved precision during the subsequent operations: machining, welding, assembly.

The workpiece in study is the Tail Bearing House (TBH) of a turbine (1900 mm in diameter, 350 mm in height and common thickness of 6-10 mm), and the machining operation to control is the turning of the flanges. This structural component is made by welding different forged and cast components that are machined afterwards. The welding produces deformations and distortions, so the fixture has to adapt the clamping of the workpiece to avoid additional deformations and hyperstatic load states in order to assure suitable precision and to fulfil the requirements for subsequent assembly process.

The precision and tolerances required in the workpiece are  $\pm 0.2$  mm for general diameters;  $\pm 0.05$  mm for reference dimensions within turned features, and  $\pm 0.015$  mm for reference holes. The fixture tolerances must be related to the part tolerances in the contact areas.

#### Proposed technical solution

In order to solve the problems and limitations explained above, it has been decided to develop a system with integrated sensors and actuators to correct and control the deformations of the workpiece while improving the precision and performance of the machining process. The development of the clamping unit has been done based on an existing flexible clamping element developed by Roemheld, adding different subsystems.

The solution comprises a series of intelligent clamping units able to detect and correct the position of the workpiece, with the following characteristics:

- Integration of sensors (displacement and force) in the clamping unit to detect undesirable deformations;
- Integration of actuators in the clamping unit to counteract the deformations by modifying and adapting the position of the jaws and the clamping force;
- Achieve an automatic position correction based on the measurement of the position and force sensors.

#### Main advantages of the solution

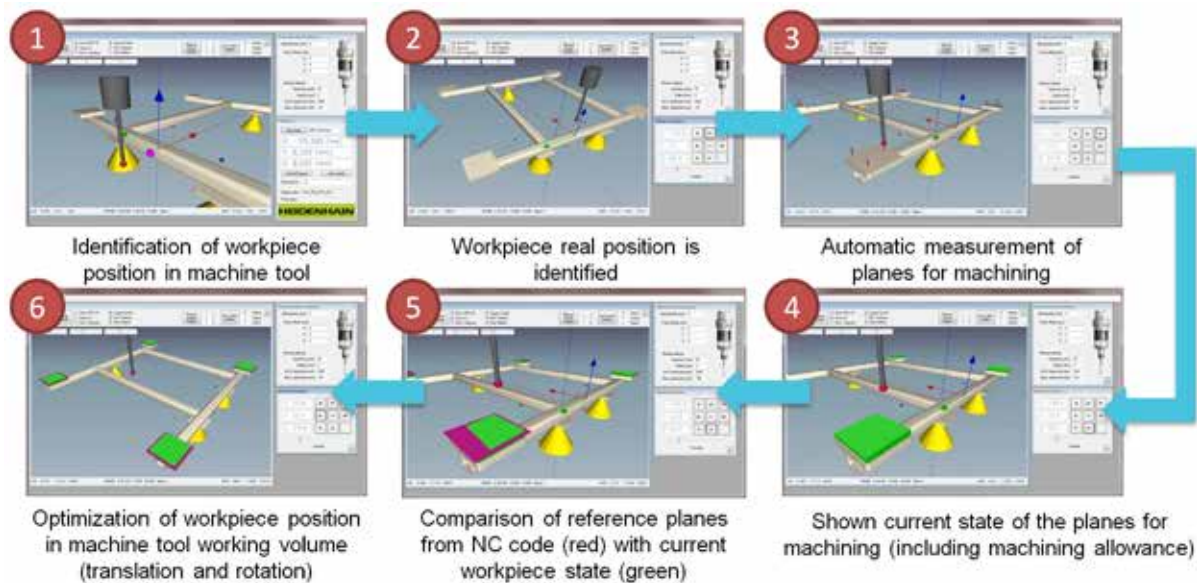
The developed intelligent clamping unit aims at substituting the current manual clamping elements in order to obtain the following improvements in the set up of the workpiece:

- Achievement of an automatic clamping and position correction based on the measurement of the displacement and reaction force in the clamping unit;
- The positioning precision of the clamping unit depends on the stiffness of the workpiece and in the case of the TBH it is below 0.01 mm;
- Using the force control in the clamping unit, it can achieve a reaction force precision of  $\pm 8$  N with a positioning repeatability within 0.01 mm;
- Using the position control in the clamping unit, it can achieve a repositioning precision of 0.007 mm;
- Reduction of workpiece exchange and set-up time by the introduction of the clamping units, being this independent of the number of units. With the developed clamping unit, it takes just 4 seconds to set up, compared to up to 15-20 minutes using the mechanical clamping elements.

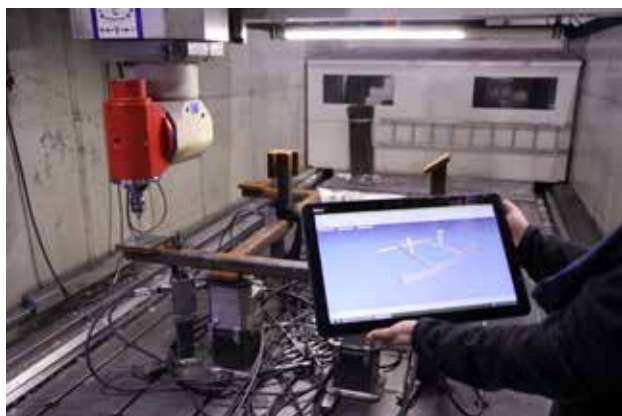
The clamping unit allows keeping the same clamping and holding forces of the mechanical units.



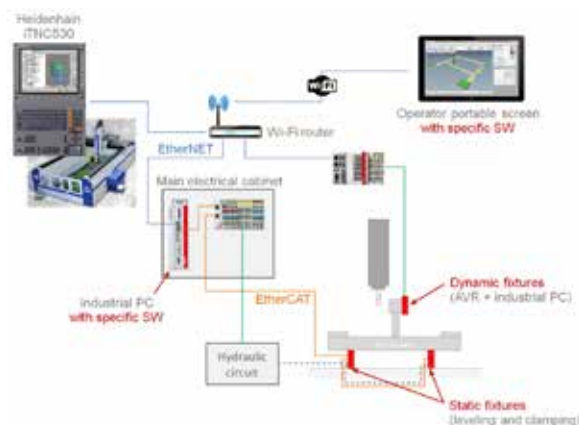




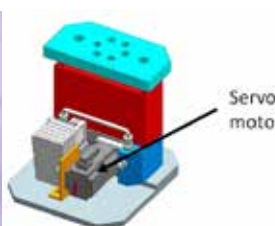
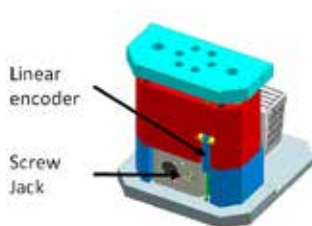
**Leveling technique in developed software LECLIN (LEveling CLamping INspection)**



**Testing in machine tool with demonstration part**



**Communication and connection scheme of the system**



**CAD models and realisation of active positioning units for workpiece automatic levelling and pre-deformation**

Parameter	Existing solution	Developed solution	Comparison
Solution	manual workpiece levelling	automatic workpiece levelling	
Total price	€5500	€10200	85%
Idle time	60 minutes	15 minutes	-75%
Invest. return level	42 pieces		

## Case study 3.1: Fixture system for workpiece adjustment and clamping with/without its pre-deformation

### Main technical issue

The case study is focused on improvement of the productivity and accuracy of large workpiece production through the shortening of the workpiece setup and clamping time. The current situation in the workpiece adjustment is based on extremely time-demanding manual setting, when the operator has to find optimal zero point of the workpiece manually – scribing operation and to fix the workpiece.

### Proposed technical solution

The new proposed solution is a comprehensive solution that automates workpiece adjustment and clamping process. It is achieved by the development of:

- **Modular active fixtures with centralized control for workpiece leveling.** Fixtures allow precise automatic positioning of the workpiece in regards to the machine tool coordinate system. The active fixtures are designed as a compact mechanism that is equipped with a ball screw connected with a servo motor, gearbox and ball nut directly connected with the movable part of the unit. The mechanism is also equipped with linear guideways for better stiffness and a brake located on the linear guideways.
- **Modular fixtures for workpiece automatic clamping in adjusted position without deformation** and with demanded clamping force. The unit for clamping in additional points consists of two main parts. The first part is an hydraulic work support that can touch the workpiece very slightly and can be fixed in that position. The second part is a swing clamp that can fix the workpiece on the work support by closing the clamping force circuit.
- **Active vibration reducer (AVR) as an alternative clamping unit** for places where above-mentioned fixtures cannot be used. It is a device composed of one acceleration sensor and one inertial shaker, within an enclosure. This device can be attached to a vibrating structure and it modifies the mechanical impedance of the structure, thus avoiding vibrations.
- **Modular fixtures for workpiece automatic clamping and its controlled pre-deformation**, the fixtures is equipped with position and pre-deformation force sensor. The fixture is a combination of the new modular active fixture equipped with a force sensor and clamping part.
- **Control system with HMI** for above-mentioned fixtures control and cooperation with a machine tool CNC. It consists of the main electrical cabinet with the main control PC (Beckhoff industrial PC) and I/O for control of hydraulic, static fixtures, dynamic fixtures (AVR), an hydraulic circuit, a portable screen with developed software LECLIN and a connection with the machine tool control system.

### Main advantages of the solution

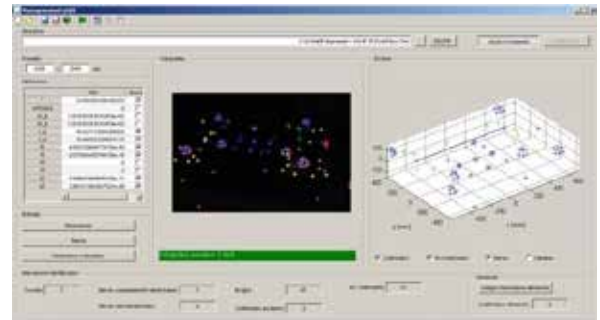
The proposed process of levelling and clamping of the demonstration part was performed in approximately 15 minutes, conventional levelling, scribing and clamping operation take about 60 min depending on the operator's skills. Based on the results, it can be concluded that the automatic workpiece levelling is much faster compared to manual levelling. Position accuracy of the unit is 6 µm with the direct position measurement system. The unit is capable to achieve 5000 N loading force during the movement, stroke 50 mm and, due to the integrated brake, more than 5000 N loading force during machining. (See table page 18)

The developed solution can be used for adjusting and clamping different workpieces which makes the solution universal. Despite the fact that the initial investment is relatively high, the proposed leveling and clamping system is cost-effective. The key financial benefits are the ability to reduce clamping time significantly and its universal design suitable for different types of workpieces.

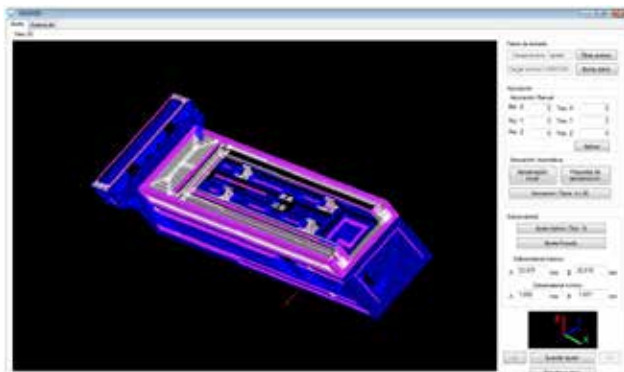




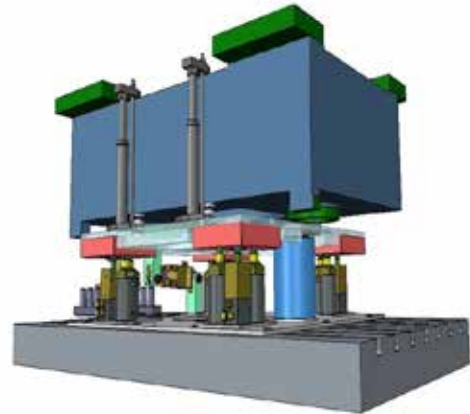
Part to be machined with photogrammetric markers (left, out-of-machine; right, on-machine)



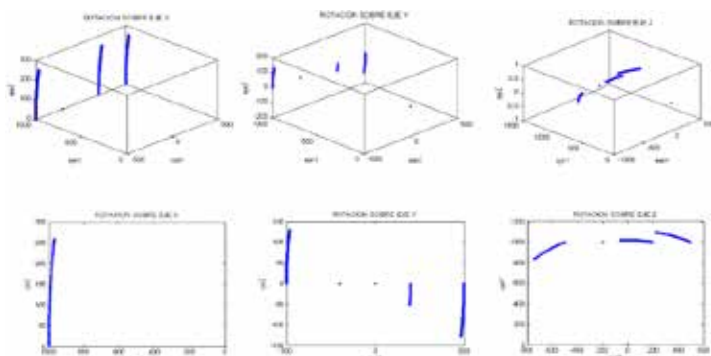
Software for measuring of photogrammetric markers



Software for best alignment of the workpiece



Alignment table, 3D model including part for test



Simulation of actuators in parallel kinematic architecture



Alignment table, final assembly



### Case study 3.2: Semiautomatic tool reference for application on large parts

#### Main technical issue

For large prismatic parts to be machined, the setup time is of the same order of magnitude than the machining process time itself, ranging from half an hour to several hours of alignment time. Besides, if this setup process has not been performed correctly, shortage of material or excessive material for machining can occur. For workpiece setup, first, a rough part is marked out according to machining allowances (excess of material to be cut). "Marking out" is the process of transferring a design or pattern to a work piece, as the first step in the manufacturing process. The rough part is positioned on a surface table and, by means of scribes, blocks, indicators, punches or compasses, some datums or references (fiducials) are marked in the rough part. Once datums are defined in the marking out process, the part is aligned according to the machine axes. Zero-point clamping systems are not used for large prismatic parts (only for very small batches or loose units), therefore the workpiece manual alignment in-machine is necessary for each unit. Using dial indicators or machine touch probes, the rough part is measured with reference to the machine axes (using the previously defined datums) and the part misalignment is obtained. This part misalignment error value is used to align the part and this process (measurement + alignment) is repeated until the alignment of the part's fiducials or marks is achieved in respect to machine axes.

#### Proposed technical solution

Alternatively to the marking-out process, photogrammetric measurement has been validated in by the INTEFIX project. A 3D metrology system based on photogrammetry technology has been developed. Algorithms and software has been developed to create a 3D point cloud of the workpiece geometry using photogrammetric markers. Software for best alignment of parts has been developed to obtain optimal alignment between the piece geometry (obtained by photogrammetry) and the CAM data ensuring there is no shortage of material or excessive material for machining. For the cases when on-machine measurement has to be carried out, an on-board camera system has been developed. The camera is clamped like a tool (using standards systems like ISO tappers or HSK), the imagining is captured by an external software synchronized with the machine, from different points and orientations thanks to the axis of the boring or milling machine. The information is sent by WIFI connection to the laptop where the photogrammetry software is running, and the results are analyzed by the operator.

Alternatively to the manual alignment, a parallel kinematic architecture alignment table to support photogrammetric results has been designed and constructed. The alignment table has 3 Degrees of Freedom and it is used for the alignment of the workpiece in relation to the three rotation axes. The movable part of the table pivots around a spherical bearing and three hydraulic actuators controlled by LVDT sensors creates the linear movements for rotation around that spherical bearing. After alignment, the whole system is automatically stiffened, ready for machining using several work support elements and actuators.

The complete system has been tested, including the automatic location of the part for avoiding material shortages at machining. This system has been validated by Goimek with different real workpieces.

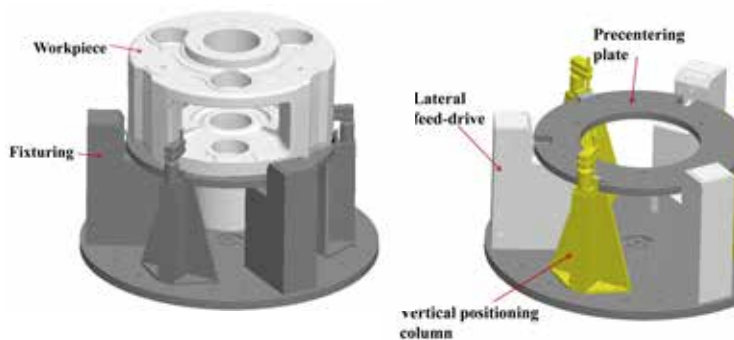
#### Main advantages of the solution

This system has three main features that makes it suitable for large parts in a manufacturing workshop:

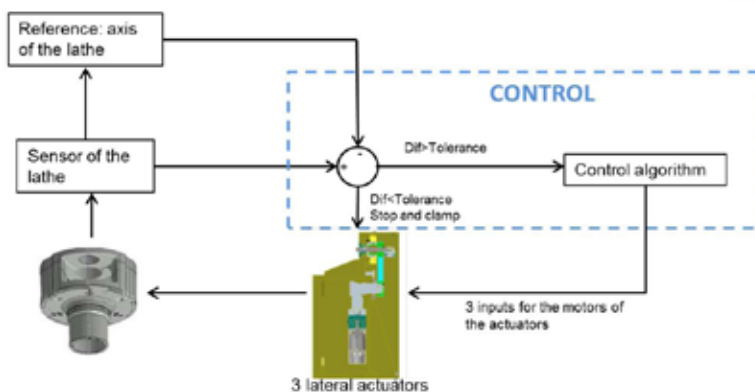
- Agility in the measurement (quick response);
- High precision in the captures thanks to the self-calibration procedure;
- The easiness to use with incremental adjustment method, making it usable by any kind of operators, without experience in photogrammetry.

This technology is less time consuming and can provide the best fit between the finished and rough parts' volumes.

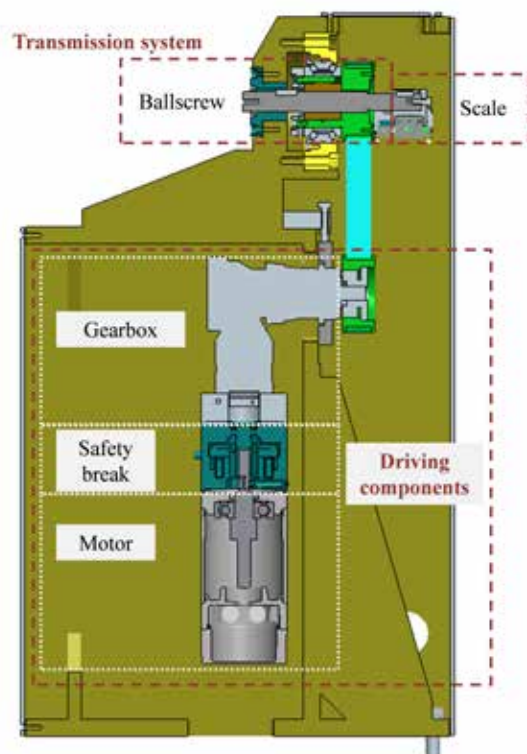




Developed adaptive fixturing with the workpiece and its components



Scheme for centering controller



Section of the feed-drive in charge of centering the workpiece



Implementation of the active fixture and the Mida WRS touch probe system into the lathe machine

### Case study 3.3: Active fixtures for high precision positioning of large parts for the windmill sector

#### Main technical issue

The machining of components such as the planet carrier for the windmills is a very demanding process. It is becoming more and more complex as larger and larger parts are being demanded which at the same time requires the machining of lighter materials/high added value added types of cast iron, like in this case Cast Iron EN-GJs-700-2. The main problems occur during the positioning of the part in the fixture before loading on the machine and the later positioning of the part within the machine reference system. The current process includes manual interventions which should be limited, since they are a source of variability depending on the operator's skills. Moreover, the need of high-precision positioning when centering the workpiece is crucial.

#### Proposed technical solution

**Workpiece clamping:** the most critical action performed by the fixture was the centering of the planet carrier with a maximum tolerance of 10  $\mu\text{m}$ . Therefore, electromechanical actuators were used because of their accuracy, high load capacity and sufficient stroke length. No feed-drive on the market was suitable for this case study, as the requirements of moving a workpiece of 3000 kg with a precision of 10  $\mu\text{m}$  by means of electromechanical feed-drives are not usual. Therefore, a specific feed-drive has been developed for the application.

**Lateral feed-drive:** in order to adjust the planet carrier laterally with a tolerance of 10  $\mu\text{m}$  in diameter, very accurate and reliable feed-drive has been designed. The feed-drive can be divided basically in three different sections: driving components, transmission system and scales. From the point of view of the control of the position, the best option was to use a synchronous motor with an encoder. The fixturing has three actuators, placed in circular shape with an angle of 120° among them. They are independent modules and can be clamped and unclamped from the base of the fixturing. Therefore the modular system can be easily adapted to workpieces with different diameters, changing radially the position.

**Control of the centering process:** to control the centering movement of the planet carrier a PID control is used in position. For the control loop, the signals of the motor encoder and the scale of each actuator, along with the signal provided by the sensor placed in the lathe, are collected and cross-checked until having placed the workpiece in the required tolerance.

#### Main advantages of the solution

The proposed solution is based on the development of a smart and active fixture valid for a family of workpieces to position them very precisely in a semi-automatic or possibly automatic way without producing any damage to the workpiece. This solution allows the positioning of the workpiece controlled by a PC with a closed loop control unit commanding the fixture. The technological development is based on the design and development of new hardware and software solutions that is based on real time data gathering by means of sensors' integration, and the development of the control system for the management of the new intelligent actuators taking also into account the machine.

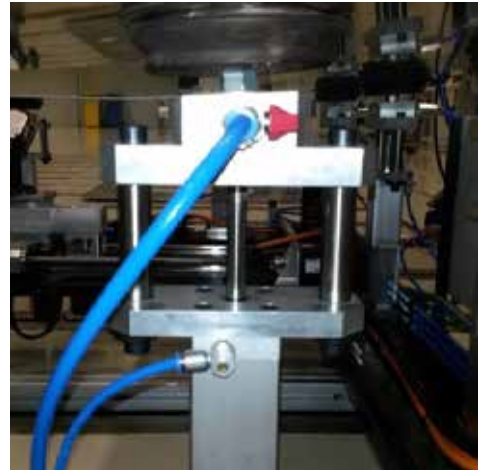
The obtained results have proved that the proposed fixture is able to center the workpiece within the tolerance of 10 $\mu\text{m}$ , assuring the quality requirements. This is possible thanks to the specific mechanical design of the actuators and their control by a PLC and a software program. Moreover, this new fixturing system allows GAMESA to increase its productivity, as the adjustment process is performed in an automatic way, reducing the setup time of 30% and the amount of defective parts. In other words, this solution increases the quality rate of the global process.



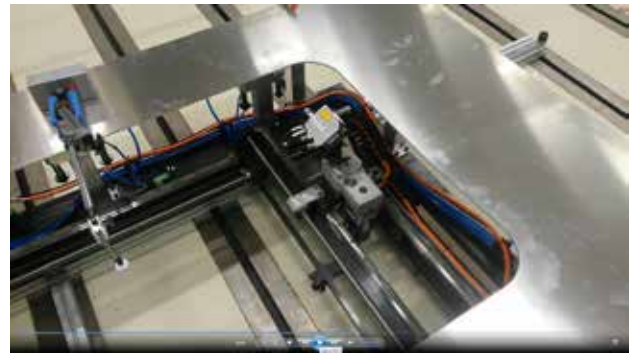




Industrial application



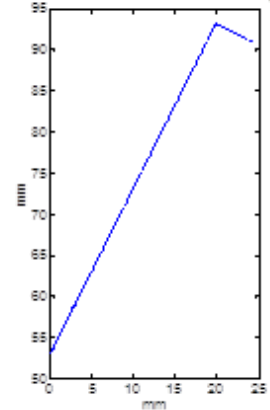
Detail of the sensor and the vacuum clamping elements



Test fixture and workpiece



Profile Measured with the Laser Scanning Sensor



Sensor during measurement and registered data

### Case study 3.4: Set-up and tool path correction of long and slender train coach structural components

#### Main technical issue

The rail industry is a strong industrial sector that generates a great income for the economies where components are manufactured, and the increase of the competitiveness a key aspect to maintain the market share of the companies.

In general, machining of low rigidity big size structural parts with the required precision is a real challenge. In the railway industry, these components are joined by welding processes, also involving many intermediate machining processes to obtain some geometric features and the final shape of the component. The process chain drives to intermediate distorted geometries and pieces prone to deformation. So, the referencing and set up of these components for the machining operations become a problem due to the distortions associated to previous processes.

The main objective of this experiment is the integration of efficient and fast measurement systems as a part of the fixture in order to improve the setup of the workpiece, adapting the tool path to the deformed geometry. The tolerance required in the machined features is  $\pm 0.1$  mm.

#### Proposed technical solution

In order to solve the problems and limitations currently observed in the railway manufacturing industry, the solution selected deals with the integration of a laser scanning sensor to check the real deformed geometry of the workpiece and adapt the tool path to the measured geometry.

The integration of different subsystems in the fixture has been done to achieve the required functionality, involving the following element:

- Integration of a movement system to control the position of the 2D laser scanning sensors in the fixture;
- Software to control the fixture, to capture the distorted workpiece geometry and to treat the data for the definition of the adapted tool path;
- Communication with the CNC of the machine tool to send the adapted tool path.

Additionally, vacuum support elements have been included to increase the workpiece stiffness in order to avoid vibration and deformation problems during machining.

#### Main advantages of the solution

Currently, in the industrial application of the experiment, the measurement is done by a slow process with touch probe systems that allow the definition of the workpiece position. This probing process currently represents up to 60% of the manufacturing time for the selected operation, the rest being for the loading/unloading the workpiece and the machining itself.

The use of efficient and fast set up processes is an important issue that could improve the performance of the manufacturing processes mainly by reducing the process time. The developed intelligent clamping unit aims at substituting the current set up process with a reduction up to just 25% of the manufacturing time.

The use of a laser scanning sensor allows the use of a large amount of data, obtaining a better and more precise characterization of the workpiece. The system allows keeping the workpiece below the required tolerance, and also avoid problems that normally arise in the curved areas of the workpiece.

Finally, the use of vacuum clamping elements allow an improvement of the workpiece stiffness. In this situation, the machining speed can be increased by 20%, so the machining time is also reduced.

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## Conclusion

The INTEFIX project carried out the development and assessment of intelligent fixtures. This activity comprises the integration of hardware elements (mainly sensors and actuators) in the fixture combined with the necessary control algorithms and automation systems to solve current limitations of machining processes for manufacturing high-added value components. The developed fixtures allow the monitoring, control and adaptation of the process to obtain suitable results according to precision, quality and cost requirements. The common functions of fixtures are improved from only securely holding and accurately locating the workpiece considered as an undeformable body, to integrate additional functions taking into account aspects like the deformations, vibrations and distortions in the workpiece during processing as a consequence of the variations in the behavior of the machining system (machine-fixture-workpiece).

The main outcome of the INTEFIX project is the integration of new and state-of-the-art technologies (sensors, actuators, control algorithms, simulation tools...) applied to the workpiece handling systems to develop intelligent and modular fixtures capable of modifying the behaviour and interactions between the process and systems in machining operations. These systems reduce time and costs with improved performance and capabilities.

The experiments carried out have resulted in a series of specific solutions to improve the limitations presented by the end users, and several generic standalone products able to perform specific task in the fixture field or more general applications.

The impact of the INTEFIX project not only trigger change in the field of machining process, as the benefits of the intelligent fixtures could be extended to other process such as welding repair, mechanical assembly, etc.



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