COMET

Plug-and-produce **CO**mponents and **MET**hods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future

Collaborative project

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1 Executive summary: thank you!

Why, you might ask yourself, am I being thanked on reading this executive summary of the COMET project? Well it is simple - this summary and all previous dissemination have been executed using funds from the European Commission. We all pay taxes and a small amount is directed to ‘Brussels’ and by reading this summary you can see what has been done with a tiny part of your tax money. So a ‘thank you’ is appropriate as it is not always clear what happens with the tax we pay. We have also used more tiny parts of your tax money for numerous other activities within our project. There are too many to mention so again, have a look at our website for the videos, press releases, and publications etc. that we have produced to make it obvious and clear to you as a taxpayer what we have done with the €5.3M of budget received from the European Commission. Of course that €5.3M has not only been spent on making videos or writing articles, it has been spent on investigations with the goal being for the manufacturing industry in Europe to start using robots to perform accurate machining operations in more rigid materials like steel and aluminium. Most of the time the manufacturing industry use milling machines which are perfectly suited to do the job, however if it was possible to use robots for certain operations then this could be more cost effective (2-5 times cheaper) and due to its layout much more flexible; it can do the handling and machining in one go! This all sounds easy but several challenges had to be overcome in the project. After working for over 30 months, a very motivated group of 14 partners have been able to demonstrate in 5 real-life case studies from different manufacturing sectors that accurate machining with robots is possible. It is not yet as common and straightforward as machining with a milling machine, but we must remember what machining with the first conventional milling machines was like compared to using today’s CNC milling machines. In the beginning it had its ups and downs but now it is common practice. This is also true of machining with robots; now it will be with ups and downs, but in the COMET project we have proved that it works. With help from a robot integrator (they are essential for the implementation of robots in your manufacturing processes and will help you ‘turn-key’) and a CAD-CAM provider you will quickly see the benefits and opportunities. Integrators and CAD-CAM providers who have been active in the COMET project can be the first point of contact to investigate possibilities with you after you have absorbed all available information on our website. We as a consortium were happily obliged to publish as much information as possible about the outcomes of our project to help you in choosing this new possibility for machining. At the same time we have learnt in the past months that we can further develop the possibilities for machining with robots by:

- Matching robot configuration strategies with milling strategies
- Effective joint management to minimize inaccuracies as a result of backlash
- Further developing an easy method to identify influencing parameters through offline compensation of robot errors
- Developing the next generation of robot controllers specifically for milling operations

Based upon a successful, motivational and enjoyable cooperation during our project life-time, the COMET partners are ready to explore these challenges in a new project and again transform them in to a commercial successes (products, services etc.) as is now happening. It has been my pleasure to coordinate (with endless support from ‘my’ Management Board members) the current partnership during this project, and I will be more than happy to do so in the future when writing, submitting and hopefully coordinating COMET-2. Maybe we have inspired you to be one of the partners.....

2 A summary description of project context and objectives

2.1 Project context

The high-end manufacturing industry requests production systems that can quickly switch between diverse machining operations with short changeover, programming and set-up times without compromising quality, reliability or life-cycle costs.

The COMET consortium aims to provide a revolutionary Plug-and-Produce solution enabling the use of industrial robots for high end machining processes, appreciating the needs from the manufacturing industry for cost effective, flexible and reliable manufacturing solutions.

This will be achieved by:

- Improving absolute positioning accuracy of industrial robots
- Enabling industrial robots to react in real time to changing process conditions
- Improving reliable programming and simulation tools to ensure first time right machining once production commences

2.2 Project objectives

- (O1) Develop and test a generic methodology to "extract" from every possible Industrial Robot configuration (for machining purposes) their kinematic and dynamic models.

- (O2) Develop and test a software suite enabling the output of 100% correct Industrial Robot Path Program.

- (O3) Develop and test a combination of hard- and software for the Adaptive Tracking of the Industrial Robot.

- (O4) Develop and test a High Dynamic Compensation Mechanism (HDCM) to compensate "remaining" position errors and enabling high precision production processes.

- (O5.1) Prove the viability of the new technologies developed in the industrial environments showing their technical and economic advantages both to the end-users and the commercialization partners.

- (O5.2) Definition of "after project life time" activities to develop the COMET outcomes within the following 12 months towards fully commercial products.

- (O6.1) Disseminate project results.

- (O6.2) Management and protection of knowledge.

- (O6.3) Development of training program to prepare for take up and use at non-consortium members.

- (O7) Ensure the smooth running and organisation of the project and to provide link between Consortium and European Commission.

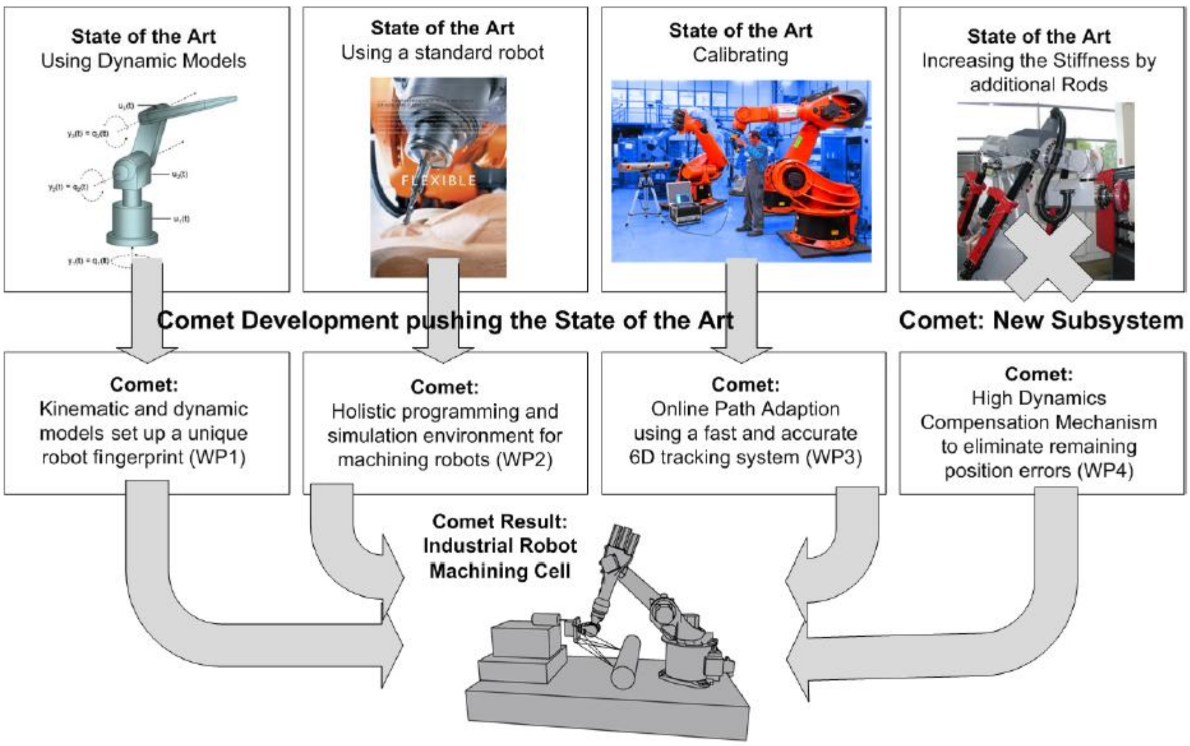


Figure 2.2-1: COMET developments pushing and setting the State of the Art

3 Main S&T results/foregrounds

3.1 WP1 – Kinematic & Dynamic Models for Industrial Robots (KDMIR)

3.1.1 Objective

Develop and test a generic methodology to "extract" from every possible Industrial Robot configuration (for machining purposes) their kinematic and dynamic models.

3.1.2 Approach

To meet this objective, this work package was split in 5 tasks:

1.1	Analysis and identification of requirements for development of the Robot Library based upon the overall system concept. The Robot Library includes further requirements for the Model Generator and the Controller Characterizer
1.2	Concept and Development of the Kinematic and Dynamic Configuration of the Model Generator
1.3	Design and Implementation of the innovative Sensor Concept
1.4	Development of the Controller Characterizer
1.5	Testing of KDMIR in research environment including adaptations to developed methodology

As the sequence noted in the table does not match the chronological order of the tasks, it is recommended for better understanding to read the results from the tasks in the following order: T1.1, T1.2, T1.5, T1.3 and T1.4.

3.1.3 S&T result T1.1

The following work was done as part of Task 1.1:

- Research State-of-the-Art: (Industrial) robot models (addressed error sources, required input, anticipated impact and developmental stage).
- Research State-of-the-Art: Process force models (as the robot's behaviour is strongly influenced by the process forces, these have to be modelled)
- Assessment of the importance of the models towards the project goals
- Determination of robot models to be implemented as part of the COMET solution the preceding analysis
- The following models were selected for integration: Optimised kinematic parameters, an empirical Cartesian compensation, a robot stiffness model, a FE robot model as well as a model for estimation of process forces.
- Derivation of a rough timeline and of the information required to be stored in the Robot Library
- Development of the Robot Library structure (including the Robot Signature in form of an XML file) and the interfaces for compensation towards the PSIR system (see Figure 3.1-1)

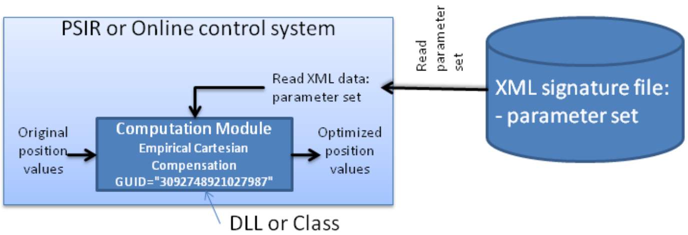


Figure 3.1-1: Proposal for basic compensation structure from D1.1

3.1.4 S&T result T1.2

The following work was done as part of Task 1.1:
The models selected in D1.1 were further investigated:

- For identification of *the optimised kinematic robot parameters* different approaches (e.g. optical measurements) are known. In T1.2 a closed-loop force-based approach was investigated and tested in simulations.
- *An empirical Cartesian compensation* was implemented and tested for free space motions. The compensation is based on static position measurements of the robot under load (using an optical measurement system). The detected deviations are stored in a compensation matrix which is used for (a) calculation of the expected deviation for a given program point and (b) for subsequent compensation of that point.
- For *the stiffness model on joint basis* further investigations were carried out, concluding that (a) joint stiffness should be considered as non-linear influence and (b) that further (non-linear) joint level effects should be considered in the model (namely joint backlash and joint stiffness). A structure for the joint-based model was proposed. Also research on identification methods for joint parameters was done, identifying two main measurement concepts: (1) stiff control and (2) stiff environment (see Figure 3.1-2). Simulations for both concepts have been carried out.
- A *FE-representation of a robot* was implemented and validated against experimental results, showing significant deviations between predicted and measured displacement.

Besides the research on the robot models, work was done on:

- Estimation of value and direction of the occurring process forces. An *empiric process force model* was developed and the first machining tests for validation have been carried out, showing the applicability of the general concept.
- Identification of possible ways to integrate the models within the PSIR workflow respective implementation approaches (implementation of model-based compensation in form of DLLs).

Figure 3.1-2: (left) Simulation of method 1: Stiff Control, (right) method 2: Stiff Environment. The solid robot image shows where the robot really is and the slightly transparent version shows where the robot thinks it is (displacements enhanced by factor 100).

3.1.5 S&T result T1.3

The models and identification methods developed in T1.2 and T1.5 were first tested in research environments (robot cells of BTU, IPA and ULund). In T1.3 these methods were applied to the industrial demonstration cells available within the project in order to be used for machining of industrial demonstration parts.

- The *identification of the optimised kinematic parameters* was carried out in 5 robot cells. During machining of the industrial parts improvements were visible (in total measures, but also in surface quality), however it became clear, that dominant joint-based errors cannot be overcome with this compensation alone.
- *The identification of the joint-based parameters using the Clamping Method* (see Fig. Figure 3.1-3) was performed in 2 of the demonstration cells. Due to the long time required for implementation and tuning of the model (and the therefore required machining experiments) and the parallel implementation of the online compensation approach (Conf. C) in one of these cells, the joint-based compensation was only used for machining of a simpler test work piece in one of the cells. The obtained results show promising accuracy improvements beyond the possibilities of the kinematic calibration. The compensation for the industrial demo part was calculated, showing the stability of the model also for large and complex work pieces.

Figure 3.1-3: Joint parameter identification using the Clamping Method at project partner SIR

3.1.6 S&T result T1.4

Despite the modelling and identification of the mechanical robot properties also the influence of the robot controller on the machining accuracy was investigated, although just in a general, high-level way. Results are some recommendations on selection of (user accessible) controller parameters like joint velocities and accelerations, rounding coefficients and the selection of proper tool path point distances within PSIR.

3.1.7 S&T result T1.5

The models as investigated in T1.2 were implemented and validated against the accuracy improvement achievable during milling. In parallel measurement methods were developed (in case existing methods were not available or not suitable) for determination of the respective model parameters.

- For *the kinematic calibration* an optical identification method to determine more suitable kinematic parameters based on a series of pose measurements was utilized. Compensation within PSIR was implemented using a sequence of kinematic transformations, using both the nominal and the optimised parameters.
- Development on both *the empirical Cartesian compensation* and *the FE robot model* was discontinued. The former did not succeed in improving the position accuracy when the milling tool was engaged in the material,

the latter suffered from the lack of suitable CAD data and the high required manual effort compared to the achievable model outcome.

- *The process force model* has been implemented and integrated into PSIR. New interfaces to PSIR (calculation of tool engagement situation) were required for this. The calculation outputs a process force vector, which is used as input for the joint-based robot simulation. A procedure to determine the required model parameters for new materials and tools, based on a test work piece, was developed.
- *The joint-based robot model* (including joint backlash, joint stiffness and joint friction, see Fig. Figure 3.1-4) was implemented using the Modelica modelling language. Based on this model a simulation of the robot movement for a given tool path is run in the Dymola simulation environment. This simulation is started by the PSIR system and is used to compensate the tool path for the predicted joint-based errors. The interaction of the simulation DLLs with the PSIR system involves several consecutive steps and thus required a large amount of work for bug-fixing of the implementation and fine-tuning of the model. For the determination of the joint-based parameters a new identification method (based on the principle of the "Stiff environment", see Sec. 3.1.4) was developed, drastically reducing the need for external measurement equipment. For this, so called, "Clamping Method" a patent has been filed.

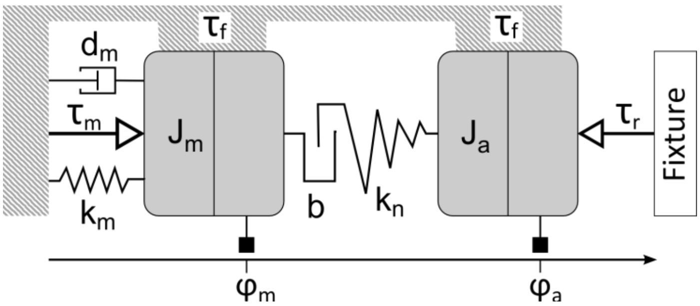


Figure 3.1-4: Schematic representation of the joint-based model components (for one joint).

3.1.8 Overall appreciation on S&T result of WP1

The work performed in WP1 of the COMET project resulted in:

- An offline kinematic calibration (comparable to State-of-the-Art), adopted for machining applications and integrated into a CAM environment.
- A dynamic robot simulation on joint-basis as well as a new measurement method for joint-level parameters, enabling the required identification with drastically reduced efforts.
- A process force calculation for machining, including a method to identify the required parameters for new materials and tools.
- (In cooperation with WP2) the integration of these models into the CAM environment (PSIR) and automated application of respective path compensations.

3.2 WP2 – Integrated and holistic Programming and Simulation environment for Industrial Robots (PSIR)

3.2.1 Objective

Develop and test a software suite enabling the output of 100% correct Industrial Robot Path Program.

3.2.2 Approach

To meet this objective, this work package was split in 7 tasks:

2.1	Requirement setting for PSIR, MTP, PAC, CMI and PAS Modules
2.2	Research for and Development of the Programming and Simulation environment for Industrial Robots (PSIR)
2.3	Research for and Development of the Manufacturing Technology Packages (MTP) Module
2.4	Research for and Development of the PAth Calculation (PAC) Module
2.5	Research for and Development of the CAD Model Interpreter (CMI) Module
2.6	Research for and Development of the PAth Simulation (PAS) Module
2.7	Testing of PSIR in research environment including adaptations to developed software suite

3.2.3 S&T result T2.1

- The main functionalities for the PSIR are determined and are broken-down into separate requirements for the individual sub-modules and structured into flowcharts.
- The five general requirements identified are:
  1. Robot tool path calculation
     a. Improve tool path output for robots
     b. Enhance kinematic solver
  2. Robot tool path optimisation
  3. Robot tool path adaption
  4. 3D simulation of complete robot machining cell
- Summary of development points for the PSIR
- The flowchart in **Error! Reference source not found.** presents the structure of the PSIR and its four sub-modules MTP, PAC, CMI and PAS.

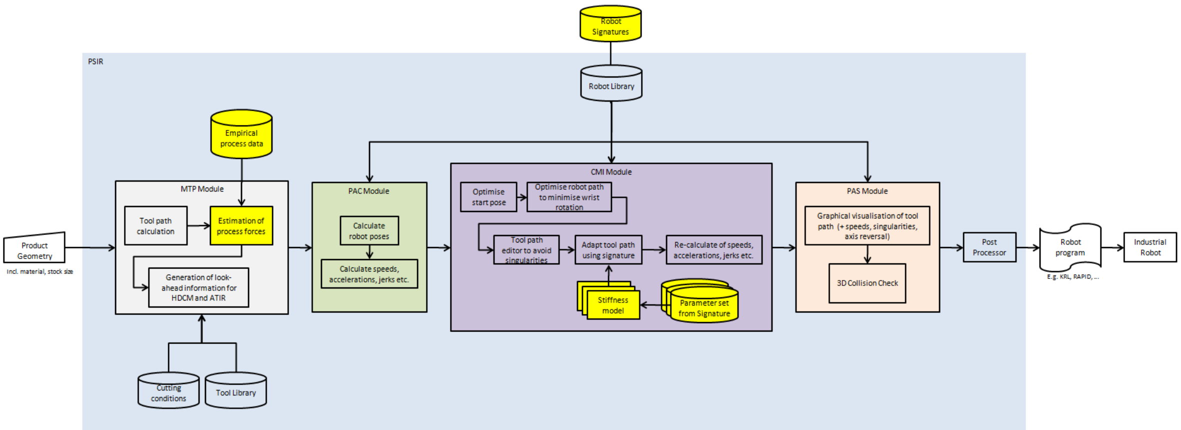


Figure 3.2-1: Overall flowchart for the PSIR and its sub-modules

3.2.4 S&T result T2.2

- The goal of this deliverable is to produce a prototype of the PSIR platform. The prototype of the PSIR will be based on Delcam's PowerMILL machining solution. The Delcam product name for the Programming and Simulation environment for Industrial Robots is the PowerMILL Robot Interface.
- During the second General Assembly meeting (November 2010) the prototype of the PSIR platform was presented to the consortium during a familiarisation training day and in the afternoon the final end-product was machined on the pilot robot machining cell at TEKS. The PSIR prototype platform was received with much enthusiasm by the COMET consortium.

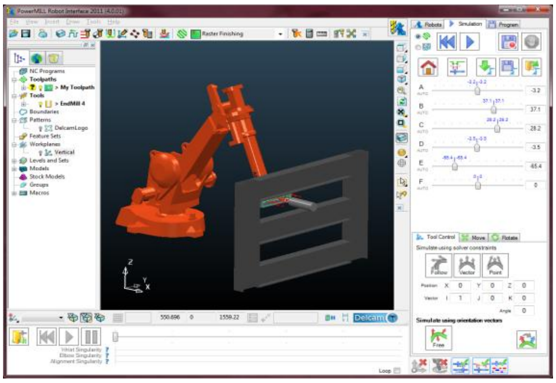


Figure 3.2-2: Prototype PSIR

Figure 3.2-3: Trainees in Birmingham during PowerMILL training

3.2.5 S&T result T2.3

- The goal of this deliverable is to produce a prototype of the MTP module.
- The operationalizing of the COMET robot machining cells within the consortium is the second major task of T2.3. All partners are involved in the task and in total eight machining cells have been setup across the consortium and the cells have been used in the different basic machining experiments.

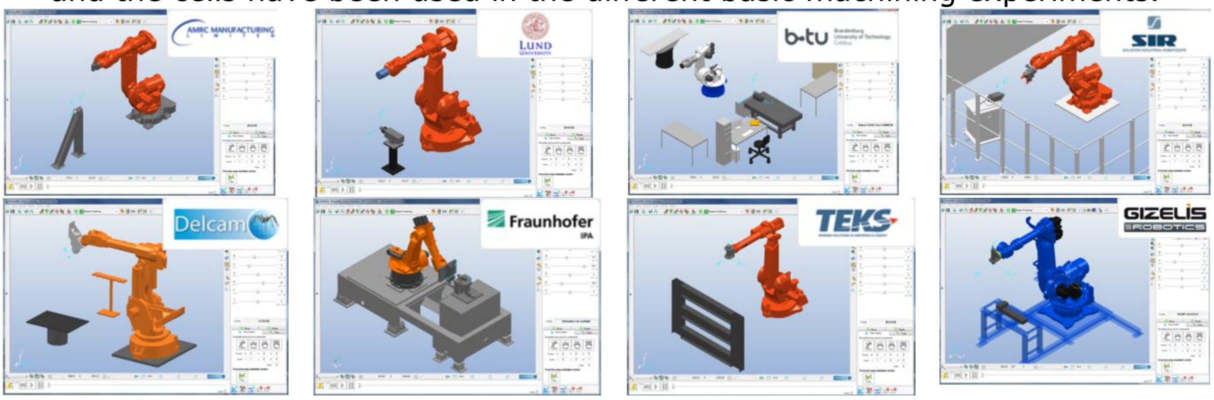


Figure 3.2-4: Eight cells setup in COMET and programmed with PSIR

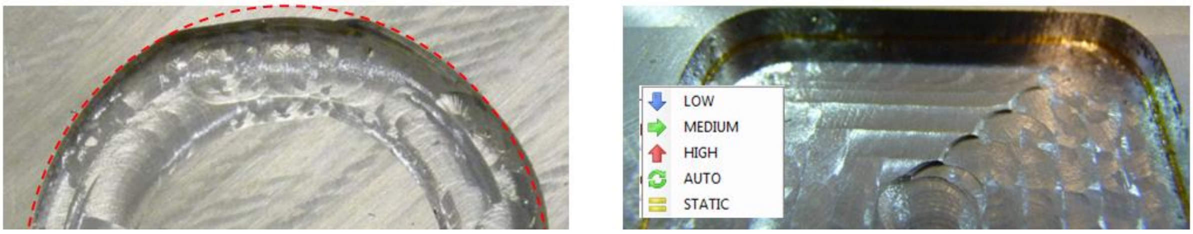


Figure 3.2-5: Backlash machining errors: large error in circular feature + step in the pocket

- The machining experiments have highlighted one major source of error, being backlash in the gears of the rotational axes of the robot, see Figure 3.2-). The experiences have fed developments in WP1 in the development of specific KDMIR models to counter backlash and other joint-effect.

3.2.6 S&T result T2.4

- The goal of this deliverable is to produce a prototype of the PAC module, which calculates the inverse kinematics to obtain the orientation of the robot arm (joint axes values) for a given toolpath in Cartesian space.
- The five main items for the PAC are:
  1. Analytical Solver
  2. Machine Entity
  3. Time-based simulation
  4. Dynamic simulation
  5. Graphs

3.2.7 S&T result T2.5

- The goal of this task is to produce a prototype of the CMI module. The main function for the CMI module is to embed the developed KDMIR models into the PSIR platform, which allow the adaptation of the robot toolpaths.
- The implementation of the KDMIR offline compensation models has been achieved by developing an external layer (COMET.DLL).
- A user interface (Figure 3.2-) simplifies the use of the models.
- For the correct operation of the compensation models, additional information such as process forces are estimated based on simulated engagement angles in PowerMILL.
- Extensive testing was needed to iron out all the numerical issues encountered. The work was a combined effort from WP1, WP2 and WP5 and in the final year all experimental work was managed together instead of separately in each WP.
- Offline compensation has been proven to work. Both the kinematic compensation as well as the joint-based compensation mechanism work and test pockets have been machined proving the dimensional accuracy improvements to within 0.2 mm (target was within 0.5 mm).

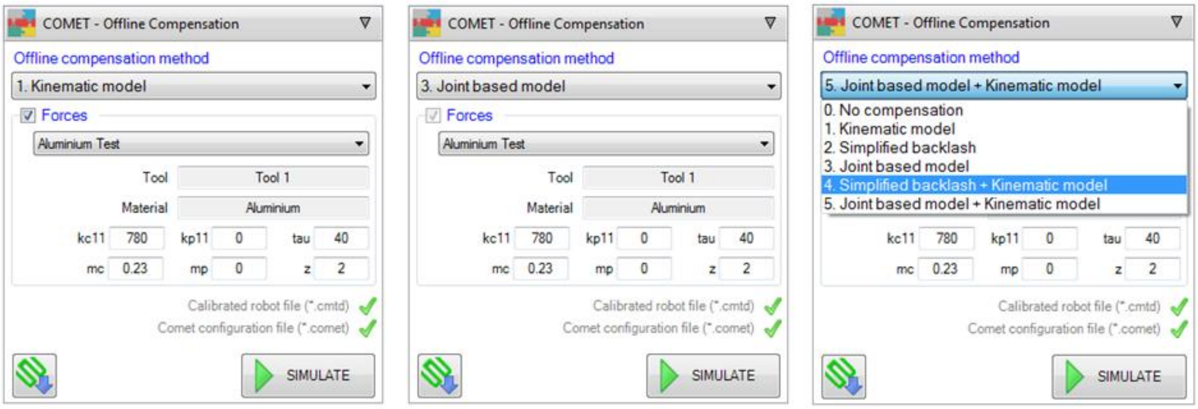


Figure 3.2-6: User interface for the COMET offline compensation module using plugins

3.2.8 S&T result T2.6

- The goal of this task is to produce a prototype of the PAS module. The PAS module contains functionalities focused on simulation and analysis.
- The simulation tools can be used to visualise the robot movements, control the remaining degree(s) of freedom by specifying constraints (e.g. locking axis A, or using a vector constraint to keep the head horizontal).
- In addition, PAS introduces various setup tools to ease the definition of the work planes on the robot cell and taking into account the tool length (Tool and Spindle calibration dialog). Of the main error sources identified, setup errors are a major error that can be avoided or minimised by a proper setup and measurement of the work planes, base and tool frame.

3.2.9 S&T result T2.7

- The goal for task T2.7 is to test PSIR in a research environment and to document the test results and propose adaptations on the PSIR based on the received feedback.
- Although continuous testing of the PSIR took place throughout the project, only in the final months in the project the overall integrated PSIR could be tested. Real demonstration sites were setup at five locations in order to machine selected demonstration geometries from the end-users.
- Machining with PSIR has been successfully achieved at the eight robot cells in the consortium. Programming using PSIR has brought already a significant improvement in comparison to traditional robot offline programming solutions.
- The major recommendation is to look at optimising machining strategies and robot strategies suitable for the robot kinematic structure and constraints in controlling all degrees of freedom. In addition also to look more at optimising machining parameters for machining with robots.

3.2.10 Overall appreciation on S&T result of WP2

Configuration A consists of the offline programming solution PSIR to generate tool paths for machining with industrial robots. Eight demonstration cells used the PSIR. Continuous testing of the PSIR took place throughout the project. Testing was performed in two ways, first of all on test geometries to understand robot machining, the achievable accuracies and secondly on real industrial parts and machining them, which validated the usage of PSIR in an industrial setting. **Error! Reference source not found.** provides an overview table of dimensions achieved on a rectangular pocket machined using Configuration A.

Pocket (absolute, mm)		Cell											
		BTU		SIR		GIZELIS		TEKS		AML		Ulund	
		Length	Width	Length	Width	Length	Width	Length	Width	Length	Width	Length	Width
Nominal		70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5
Config A		69,5	37,74	69,9	37,7	69,95	37,45	69,24	36,95	69,82	37,45	68,01	35,45

Pocket (delta, mm)		Cell											
		BTU		SIR		GIZELIS		TEKS		AML		Ulund	
	DOW	Length	Width	Length	Width	Length	Width	Length	Width	Length	Width	Length	Width
Nominal		70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5	70,0	37,5
Config A	5 - 1 mm	0,500	-0,240	0,100	-0,200	0,050	0,050	0,760	0,550	0,180	0,050	1,992	2,051

Figure 3.2-7: Overview table of realised pocket dimensions using Configuration A

3.3 WP3 – Adaptive Tracking system for Industrial Robots (ATIR)

3.3.1 Objective

Develop and test a combination of hard- and software for the Adaptive Tracking of the Industrial Robot.

3.3.2 Approach

To meet this objective, this work package was split in 4 tasks:

3.1	Requirement setting for ATIR including sub-requirements for the Tracking system and CPA Module
3.2	Research for and Evaluation of the Tracking system
3.3	Research for and development of the Comparison and Path Adaptation (CPA) Module
3.4	Testing of ATIR in research environment including adaptations to developed hard/software

3.3.3 S&T result T3.1

- *Verification and confirmation of the requirement as defined in the COMET "Description of Work"*

The requirements as set out in the COMET "Description of Work" were confirmed. The tracking system research started from Nikon Metrology's K-Series system, see Figure 3.3-1. It enables the accurate determination of actual position, speeds and accelerations of tools during the machining process, hence provides tracking in 6 dimensions. It is an external system that can be attached to any possible industrial robot configuration.

Figure 3.3-1: K600 Camera

3.3.4 S&T result T3.2

- *Latency reduction through centroid calculation performance improvement.*

Development of a new interface that provides direct access to the XYZ position of each marker to an external application over an UDP socket. Data is provided immediately after the marker acquisition.

- *Accuracy improvement through new calibration method and new centroid calculation algorithms.*

The method is implemented in a limited working volume. The new calibration method also improved latency thanks to increase in calculation speed.

- *Tracking system cost analysis. Further costs saving initiatives are identified.*

- *Development of tracking system prototype*

Nikon Metrology implemented the T3.2 results in two prototype tracking systems.

3.3.5 S&T result T3.3

- *Feasibility testing at Nikon Metrology*

Path tracking tests at Nikon Metrology showed that there are a number of problems to be overcome in order to correct for the micro deviations in a robot path. Therefore two methods were investigated: real-time online compensation and iterative learning control. Figure 3.3-2 shows the CPA scheme and its relation to the robot and robot controller for both methods.

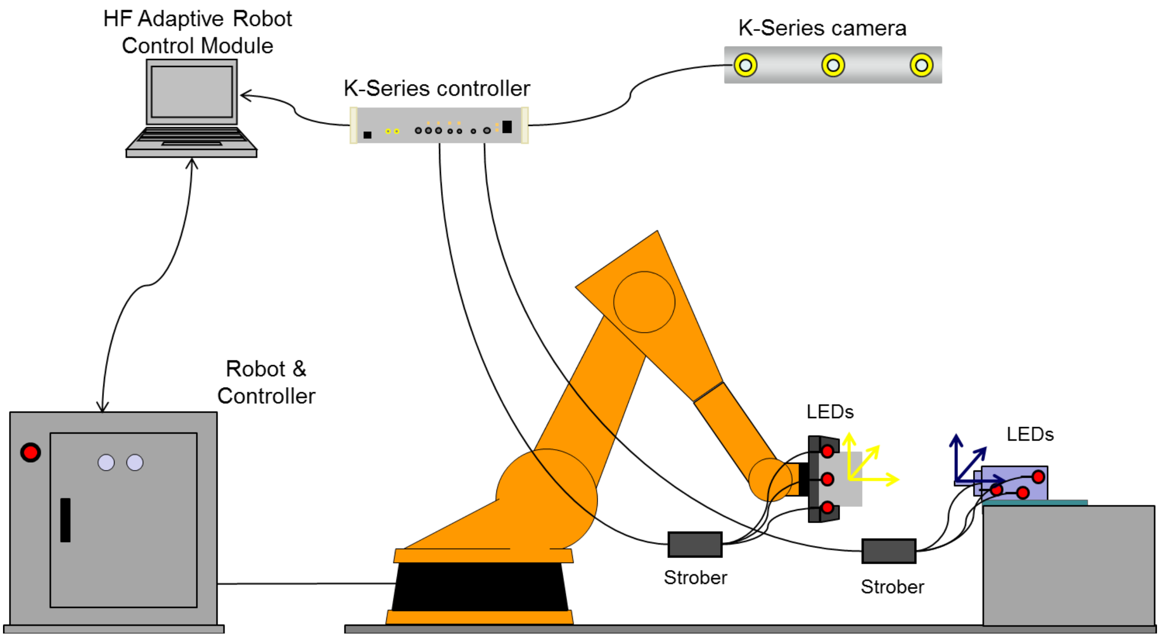


Figure 3.3-2: CPA Scheme and its relation to the robot and robot controller.

- *Real-time online compensation*

A prototype implementation for real-time online compensation with the K600 system was developed at Lund University. Figure 3.3-3 shows the setup. The deviations of the robot TCP is measured and fed online to the robot controller, whereby corrections were performed.

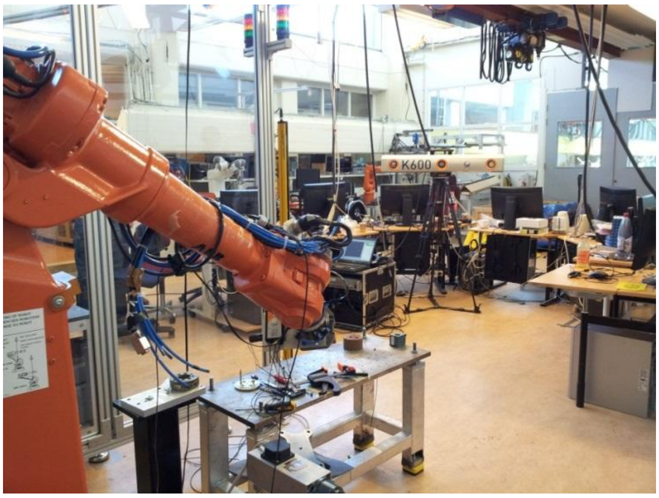


Figure 3.3-3: Set-up of the ATIR in the robot cell at Lund University

A second prototype implementation for real-time online position compensation with the K600 system was setup at Fraunhofer IPA, see Figure 3.3-4. The tracking system was interfaced to a Beckhoff controller which is used for the control of the KUKA KR125/1 robot in their lab.

- *Iterative learning control*

The iterative learning control approach is an offline method as opposed to the real-time compensation approach described in the previous paragraph. In the iterative approach, the position and orientation errors of the robot are measured online using the optical tracking system. Subsequently, in the offline stage, the reference tool path for the machining is updated for the next run, using the low-pass filtered position error measured during the first execution. The iterative learning control approach was installed at the demonstrator sites at AML and SIR.

- *Smart splitting algorithm*

In the standard real-time CPA approach, the corrections of the robot position are achieved without external compensation. To compensate for high-frequency position errors and transients, the HDCM, developed in WP4, is to be used. When the optical tracking system is utilized together with the external HDCM unit, the corrective actions during the milling task need to be achieved by a combination of actuation with the robot and the HDCM. Whereas the latter has a fast, but geometrically limited, compensation range, the robot is comparably slow but has a larger workspace. Therefore, a smart frequency separation control structure is proposed for controlling the robot and the HDCM in order to make sure that the HDCM operates within its work range.
The research was conducted at Fraunhofer IPA in collaboration with Lund University and implemented at Fraunhofer IPA, see Figure 3.3-4.

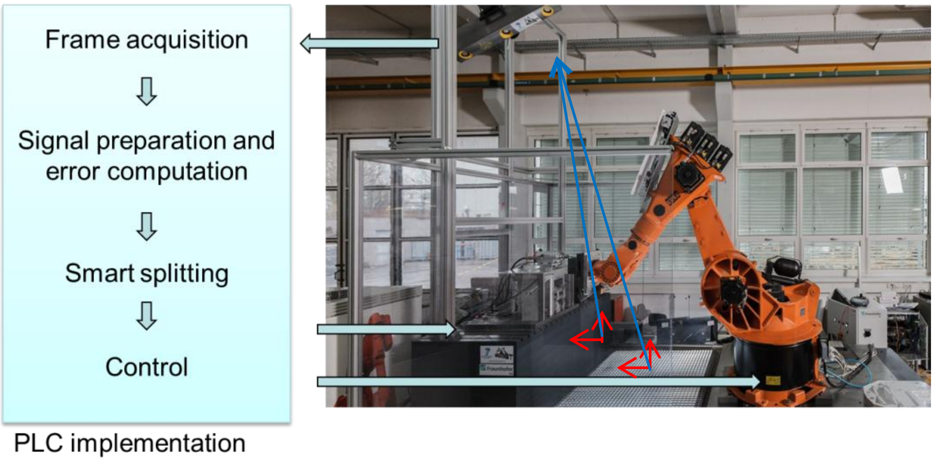


Figure 3.3-4: Test setup at IPA.

3.3.6 S&T result T3.4

Nikon Metrology tested the results of T3.2 in the research environment using the prototype system on latency, accuracy and performed risk analysis, conformity to CE norms and security.

- *Validation of the latency of the system*

Measurements are taken with a K600 camera prototype. The resulting system latency is about 500 µsec for a single LED.

- *Validation of the accuracy of the system*

The new calibration method is verified based on a comparison between calculated XYZ (from 3 lens centroids) and CMM position.
The final system shows an accuracy improvement of 20%, and even of 50% for short range measurements up to 20 mm in X and in Y and up to 60 mm in Z.

- *Risk analysis, conformity to CE norms and security*

Risk analysis, and conformity to CE norms and security were investigated and confirmed.

3.3.7 Overall appreciation on S&T result of WP3

In WP3, new prototype tracking systems were developed with low latency and increased accuracy.
These systems were first tested in the research environment, then used in the development of the CPA. Two methods were investigated: real-time online compensation and iterative learning control. Milling results prove the target gain in accuracy through adaptive tracking.
To also compensate for high-frequency position errors and transients, the HDCM, developed in WP4, is to be used. In WP3, the CPA functionality required to interface with the HDCM control, was developed.

3.4 WP4 – High Dynamic Compensation Mechanism (HDCM)

3.4.1 Objective

Develop and test a High Dynamic Compensation Mechanism (HDCM) to compensate "remaining" position errors and enabling high precision production processes.

3.4.2 Approach

To meet this objective, this work package was split in 5 tasks:

4.1	Analysis of environments and use cases, definition of requirements and deduction of realization concepts
4.2	Construction and finite element optimization of a HDCM
4.3	Manufacturing, control of the actuators and sensor data processing for the HDCM
4.4	Development of control algorithms for the HDCM
4.5	Testing of HDCM in research environments including adaptations to developed hard/software

3.4.3 S&T result T4.1

- Discussion of interaction scenarios taking into account flexibility and work space of the robot machining system
- Definition of requirements regarding precision, loads and interfaces
- Definition of test work pieces
- Concept of actuation principles of the HDCM: Actuators, bearings and sensors
- Control concept in order to reveal the full performance of the HDCM

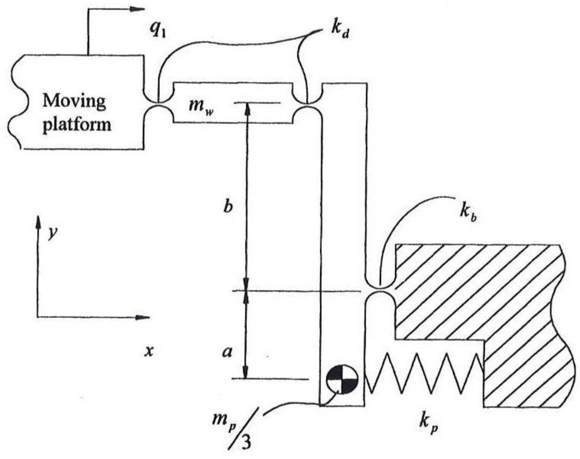


Figure 3.4-1: Flexure concept to realize the bearing of the HDCM

3.4.4 S&T result T4.2

- *Manufacturing validation:*
  Development of a new actuation principle of the spindle in order to reduce the moved mass and to increase the bandwidth of the system.
- *Construction method of the new HDCM:*
  Construction method based on elastic solid state joints investigation and its shapes to set-up a stiff construction except the needed flexibility in each direction of the provided direction.

- *Finite element optimization of the new HDCM:*
  Iterative design procedure was improved taking into account finite element analysis. This allows the better understanding of the flexibility of the axes and its transfer of rotational to linear movements.
- *Technical drawings and specification:*
  The possibility of manufacturing the parts of the HDCM in small batch production was evaluated.

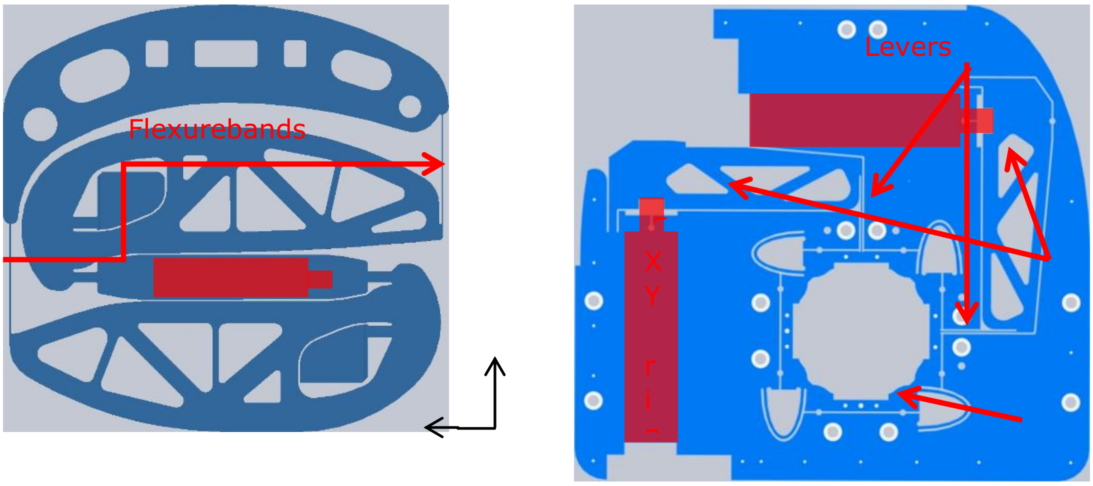


Figure 3.4-2: Z/XY actuation of the HDCM

3.4.5 S&T result T4.3

- *Manufacturing Validation -*
  To investigate the manufacturing some experiments were successfully accomplished. These experiments showed that the used machines achieve the specified tolerances in particular for the thin and complex geometries. Furthermore the machining of big parts like the height of the double lever part, shown in **Error! Reference source not found.** was confirmed.
- *Metal Works -*
  The complex new design of the HDCM was completely manufactured. Regarding undercuts and the elastic solid state joints electric discharge machines were used. Fur the roughing and finishing CNC-milling machines were applied.
- *Sensor and actuator integration -*
  The capacitive sensors and the piezo actuators were integrated. Pressure plates of hardened steel are assembled and calibrated to pre-load the piezo actuators. First travel test were successfully conducted. The HDCM solution is depicted in Figure 3.4-3.

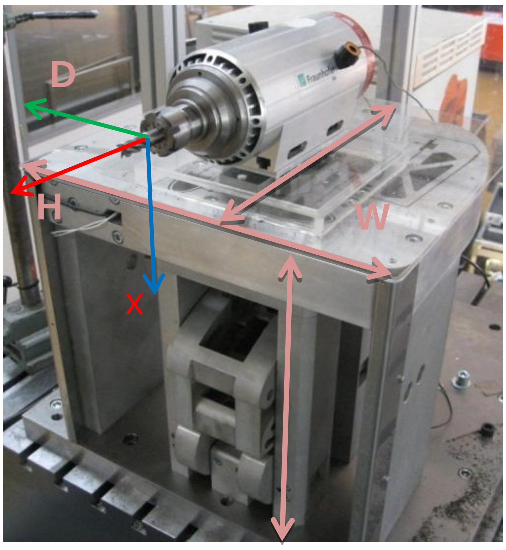


Figure 3.4-3: HDCM solution with three perpendicular compensation axes.

3.4.6 S&T result T4.4

- Frequency analysis of the HDCM: inner loop, outer loop and couplings
- Modelling of hysteresis and usage of inverse model in feed forward branch
- Model of the dynamical behaviour
- Controller development: Optimal controller based on LQG and PID, see Figure 3.4-4.
- Validation of controllers in research environment

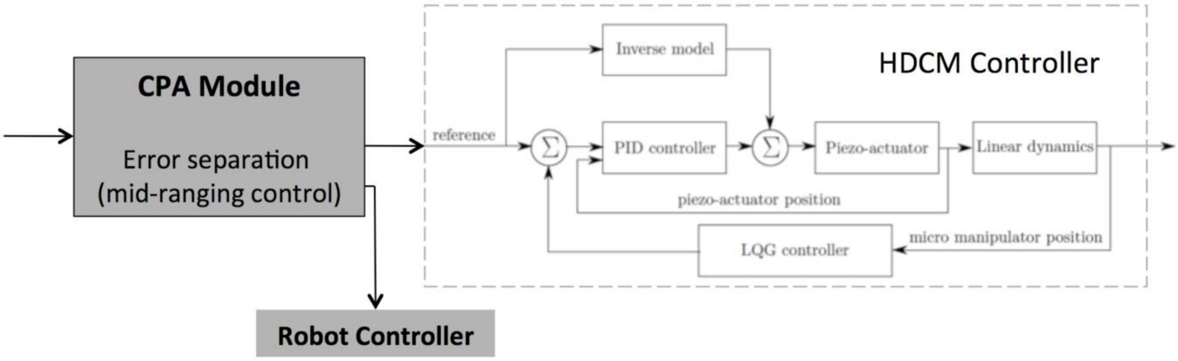


Figure 3.4-4: Control concept for the feedback control of the spindle position

3.4.7 S&T result T4.5

- Harmonization of cell components: robot, robot controller, PSIR, ATIR and HDCM
- Interfacing of measurement system and robot controller
- Integration of smart splitting functionality between robot and HDCM: This allows keeping the robot in the compensation range of the HDCM.
- Evaluation of the entire system in machining operation

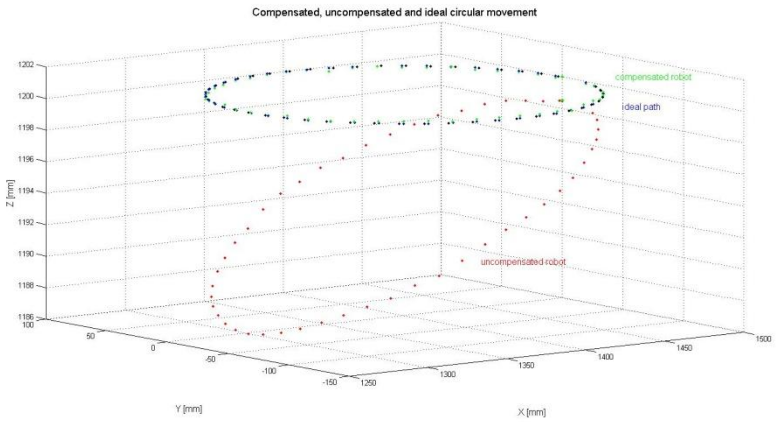


Figure 3.4-5: Measurement result of complete setup: Robot, ATIR, HDCM

3.4.8 Overall appreciation on S&T result of WP4

In WP4, new prototype of HDCM system was developed and designed with high positioning accuracy and high bandwidth to sustain process forces and compensate remaining errors during machining process.

After elaboration of the technical requirements a machining methodology was achieved to machine such HDCM. The HDCM was assembled and it was first tested in the research environment. As the proper demonstration of the HDCM needed a running configuration D, see Section **Error! Bookmark not defined.Error! Reference source not found.**, the CPA functionality was adapted and required interfaces to robot controller, ATIR and HDCM harmonized. Concerning the online compensation the feedback control was investigated and refined to allow a synchronised compensation between robot and HDCM. Milling results of a circular path prove the research approach and good tool path constancy see Figure 3.4-5.

Measurements on a CMM show the improvement by the feedback control. The mean absolute error improved from 255 µm (uncompensated) to 32 µm (controlled HDCM plus robot).

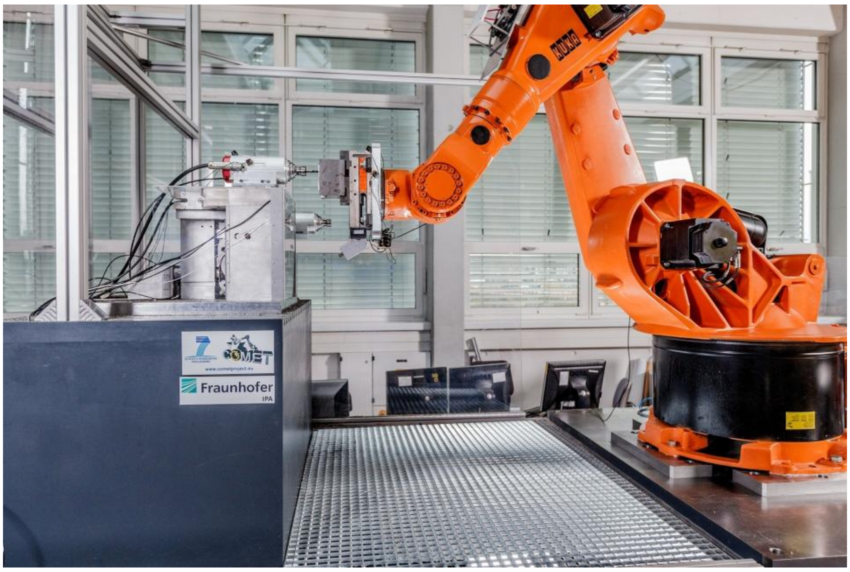


Figure 3.4-6: IPA demonstration cell with all harmonized components

3.5 From KDMIR, PSIR, ATIR and HDCM to Configurations A, B, C and D.

The intrinsic modular approach adopted in the COMET Project lead to the development of 4 main architecture configurations (A, B, C and D). Such configuration based design approach was carried out to identify and focus on exploitable results and business models and, at the same time, to lead to a leaner and more efficient management of all the different research activities. In the second half of the project these architecture configurations were developed and their performance investigated on real demonstration cases.

Configuration A

The configuration A is based on the PSIR package and it will be the basic COMET solution. Potential exploitable results may lead to an effective and easy to use robot machining solution with limited cost of investment and reduced variable costs. In fact, PSIR ease of use and robot knowledge assisted simulation will noticeably decrease the time needed to optimize the robot machining process and program the robot cell respect state of the art. The special needs and robot control features are now accurately taken into account and guide the software assisted procedures. This solution proved to improve the potential of robot machining applications, from cell setup to optimization of the machining cycle ad robot programming and it can be effectively used by both system integrators and final users. Even if the robot is evaluated as ideally stiff and precise (that is far from reality) the robot machining process planning leads nevertheless to important performance improvements.
Respect to the state of the art many important improvements have been developed with tangible results in terms of improved final machining accuracy and overall time needed to setup and realize the machining (i.e.: variable cost of application): such solution may be evaluated as a exploitable result by itself.

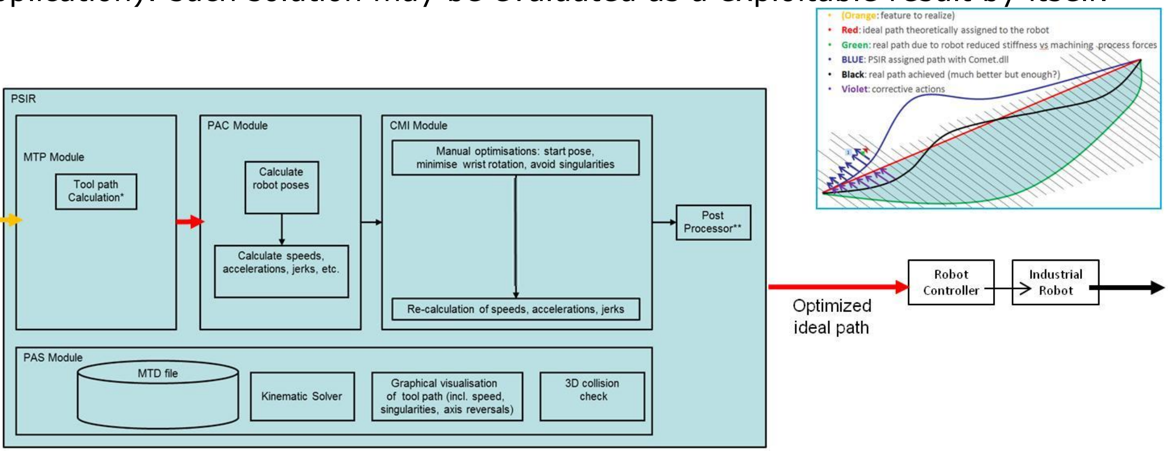


Figure 3.5-1: COMET system architecture configuration A

Configuration A provides a predictive offline process design approach using customized robot machining strategies <u>and</u> evaluating 'reachability' and robot limits in a virtual environment. Starting from the workpiece, a proper computer aided procedure assists the user in developing a complete robot machining cycle.

Latest CAM technologies are seamlessly embedded into modern Robot Offline simulations tool. Specific tools identify most important robot motions accuracy errors and support the user in the generation of alternative, improved accuracy trajectories. Once the machining process is optimized a robot vendor proprietary language part program is automatically created and sent to the robot controller for immediate use. Cell setup and calibration tools and procedures enable accurate fitting between virtual simulation and real robot cell.
Configuration A results provided important achievements not only in terms of improved accuracy but also ease of use and reduction of time needed to define, program and setup the robot machining.

Configuration B
The configuration B benefits from KDMIR that predicts robot motion errors and provides offline predictive error compensation. The KDMIR module is embedded as add on in the PSIR package which now evaluates also the real behavior of the robot due to kinematic and dynamic errors. Such errors are the main limit of robot machining compared to machine tools.
Three different solutions were developed: a kinematic robot signature model, a dynamic model evaluating only a simplified model of backlash (resulted as the primary source of errors) and a fully dynamic Joint Based model. These solutions require calibrating the robot(-cell). Together they form the KDMIR and are represented in grey in figure 1-8. This will raise the investment costs of potential exploitable results as the robot kinematic and dynamic calibration requires special hardware tools (only simplified backlash option does not need additional special hardware) and specialized highly skilled operators. But the achievement of a higher accuracy is the gain of this investment which enables new applications, once unfeasible.

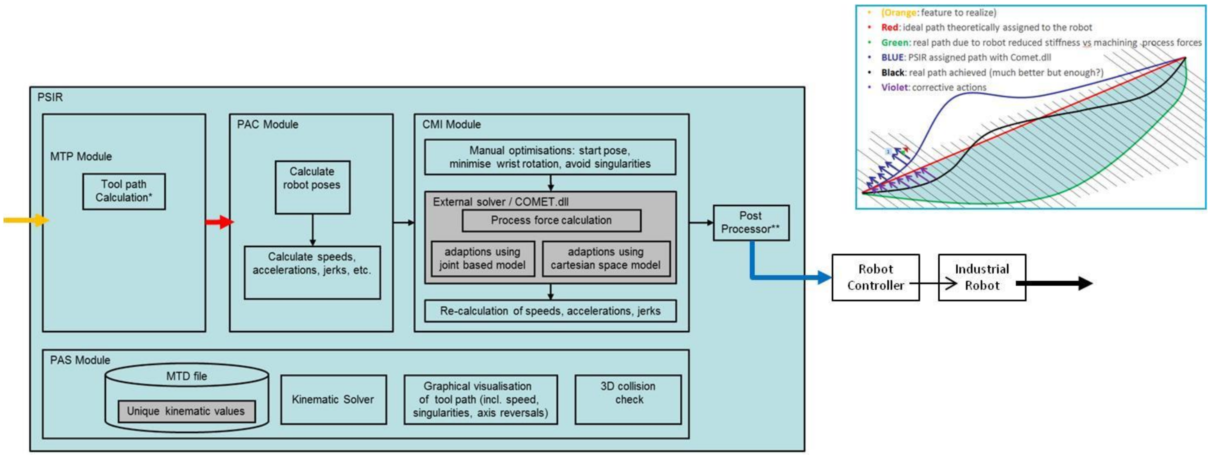


Figure 3.5-2: COMET system architecture configuration B

Since KDMIR predicts robot motion errors, an alternative compensated path (shown in blue) is loaded in the robot controller: the calculation and determination of the compensated path is a strong change with the current state of the art. An external solver ("comet.dll), embedded in the PSIR, is used to define and calculate the compensated path.

Kinematic models and 'measurements' methods were developed to evaluate and take into account the errors and deviations from the nominal ideal robot geometry and proved that real robot geometries. A calibration procedure was developed and calibrations were performed in several COMET cells. A custom procedure was also developed to determine the compensated path to be taught to the robot controller, special software to support and automate this procedure will assist the users avoiding potential errors.
Simplified Backlash models were developed to evaluate backlash effects only, identified as the primary source of motion errors. As shown in WP2 report the predictive models are effective and experimental test are confirming important accuracy improvement.
An important and very innovative calibration method was developed and is now under patenting. Configuration B demonstration on COMET Cells confirmed the goodness of the approach and the potential on real industrial applications.

Configuration C

The configuration C innovation is the online sensing of the real position of the robot-end-effector for giving a real absolute accuracy position feedback to the robot controller, such feedback may be given in real time or as a reference for the "next piece" machining. The technological core of the solution is the ATIR, a high performance tracker connected with the robot controller.

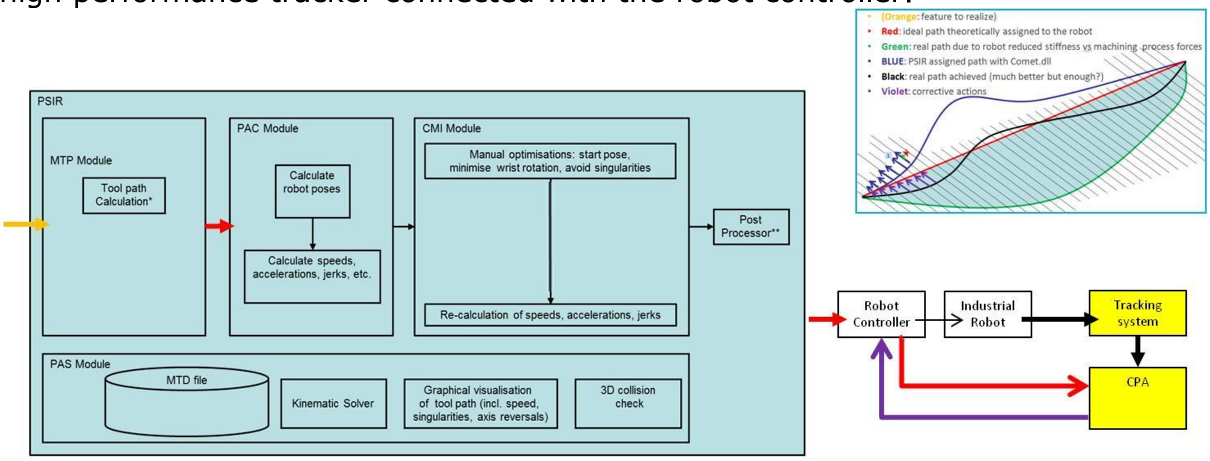


Figure 3.5-3: COMET system architecture configuration C

Once the robot program is realized with PSIR (as in Configuration A) and loaded in the robot controller, the robot will perform the machining. The tracking system will sense the real position of the robot-end-effector and the CPA module will synchronize with the robot controller and feedback real positions values or store the real positions for generating a better adaptive path ("next piece" option).

ATIR had to face important challenges in terms of superior sensing accuracy and feedback integration with robot controllers. Especially the last is more difficult than expected. Sensing accuracy and latency were achieved investigating many different design variants, unfortunately the cost reduction targets were not accomplished but the target performance were achieved.

Online real time integration with robot controllers has been demonstrated with ABB IRC5 controller, available in Lund and with the custom designed IPA Beckhoff controller. The proof of concept of the integration of a robot with a superior accuracy external sensor will open new application fields and stimulated robot vendors to improve their proprietary controllers.

Configuration D

The configuration D is a further enhancement of configuration C: in fact the robot errors compensation is performed not only by the robot but also, with shorter stroke and higher frequency, by the HDCM. CPA and splitter modules connect HDCM with ATIR and separate different corrective actions between robot controller and HDCM actuators.

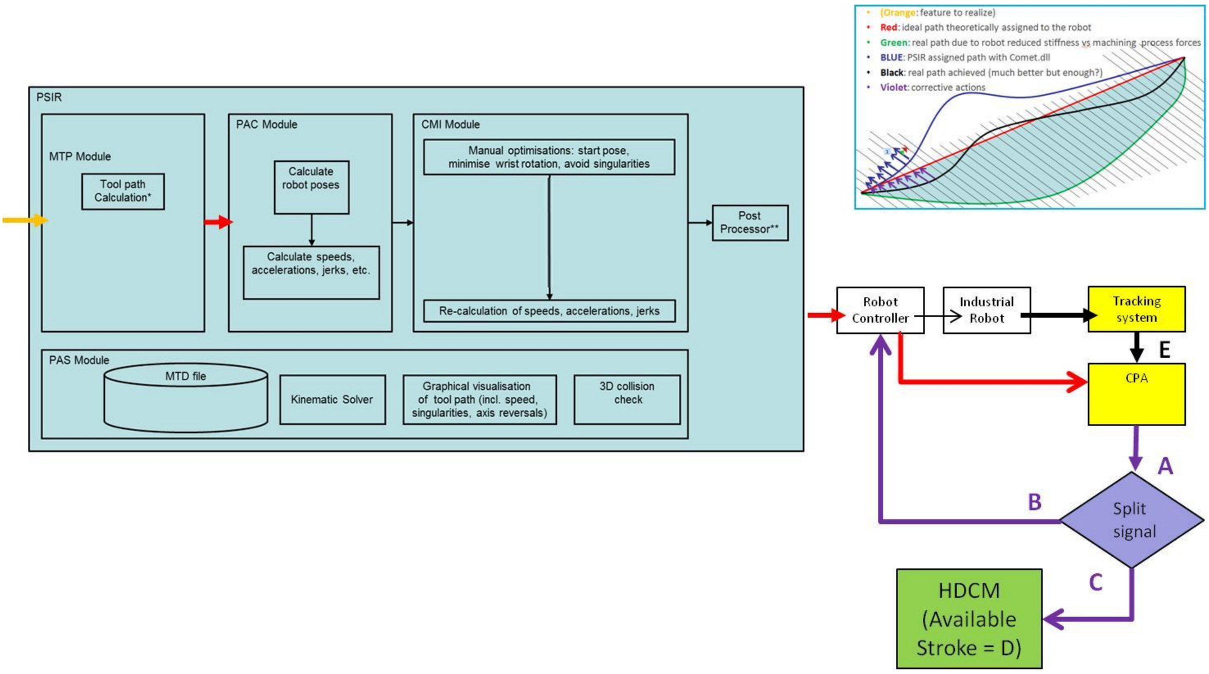


Figure 3.5-4: COMET system architecture configuration D

The validation of HDCM actuators and motion control was finally achieved proving the effectiveness of the hard work performed and the radical design changes introduced to increase robustness and performance of the piezo-actuated high precision mechanism.

The integration with ATIR was realized by syncing different controllers with different protocols and field buses. The CPA module developed adaptive control correction strategies. Final machining tests proved to gain a final work piece accuracy comparable to medium precision machine tools, accomplishing the COMET project ambitious final target. Experimental results showed to reach 0.047mm accuracy on Aluminum work pieces.

3.6 WP5 – Demonstration of COMET approach (DEMO)

3.6.1 Objective

Prove the viability of the new technologies developed in the industrial environments showing their technical and economic advantages both to the end-users and the commercialization partners.

3.6.2 Approach

To meet this objective, this work package was split in 5 tasks:

5.1	Case study components and report: aero components
5.2	Case study components and report: automotive components
5.3	Case study components and report: high precision components
5.4	Case study components and report: mould and die components
5.5	Definition of 'after project life time' activities to develop the COMET outcomes towards fully commercial products

3.6.3 Outcome T5.1

Partners TEKS and AML tested COMET approach on two different demonstration cases linked to aero – components sector: to full machine a wing's component from an Aluminium block (TEKS) and to debur root slots typically present in Inconel turbine discs (AML).
TEKS used an ABB robot, with spindle hold by the robot. Configuration A and B (kinematic model) have been set up. The full machining process has been successfully tested with Configuration A and B.
Main outcomes from demonstrations are the followings:

- Accuracy reached with Configuration A and B are compatible with roughing machining specifications; Configuration B showed accuracy improvements respect to Configuration A
- Equipment cost reduction is a strength point respect to CNC (30-40 % less)
- Process costs are comparable to CNC because of the slower cutting process
- Working envelope (50% more) and flexibility (virtual palette changer mode allows parallel processing of parts) are strenghts points compared to CNC.

Figure 3.6-1 left: TEKS COMET cell; right: Aluminium wing's component machined by robot

End user recommendations after demonstration test are to use robotic milling solution for roughing machining. Choosing the right payload for the robot allows achieving higher cutting depths and feed rates, so having faster and more competitive cutting processes.
AML used an ABB robot, with part hold by robot. Configuration A, B (kinematic model) and C have been set up. The deburring process has been successfully tested with Configuration A and B.
Main outcomes from demonstrations are the followings:

- Accuracy with Configuration B Kinematic model showed improvement respect to Configuration A; well better than current manual process, still not comparable with CNC
- Costs of the process are more competitive than CNC through reduced initial setup costs and reduced consumable costs (energy)
- Flexibility of a robot cell can allow multiple setups within the increased working envelope
- A reduced factory floor space can allow increased number of cell within the same space as a CNC competitor for large scale production

Figure 3.6-2 left: AML COMET cell; right: microscope image of deburred edge of test part feature

COMET approach has demonstrated the potential of robot machining for deburring Aerospace components. Accuracies shown for configuration A and B can already match that required by the current manual method while further developments of Configuration C will allow reaching the requirements for a fully automated process.

3.6.4 Outcome T5.2

Partner SIR tested COMET approach to machine an Aluminium cast brake calliper (see **Error! Reference source not found.**).
Goal was to fully automate the cast part finishing, with 15 operations on the 4 sides of the part (Face milling, contour milling, drilling and chamfering), from part grasp to final quality control (vision system).
An ABB robot cell has been used, with part hold by the robot. Configuration A, B and C has been set up. The full machining process has been successfully tested with Configuration A. Main outcomes from demonstrations are the followings:

- Accuracy: Configuration A hit geometrical tolerances, while for dimensional ones Configurations B and C are needed.
- Process cost reduction respect to CNC (50%) thanks to automated process

- Higher changeability and flexibility respect to CNC
- Wider working envelope respect to CNC

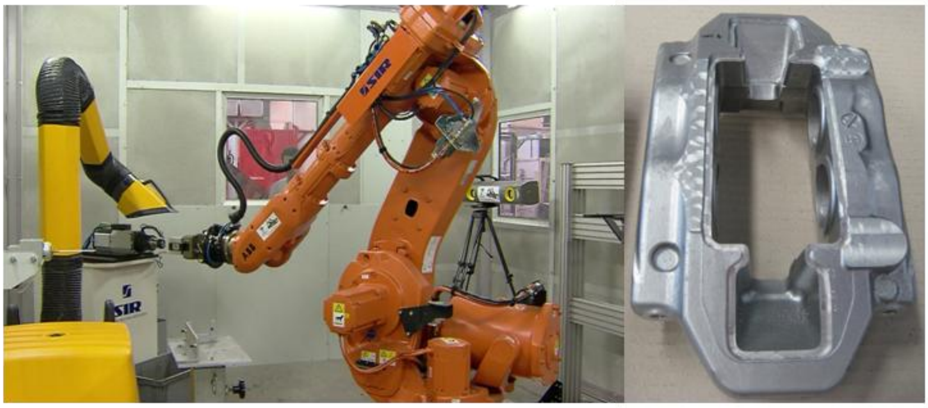


Figure 3.6-3 left: SIR COMET cell; right: cast brake calliper machined by robot (chamfered)

COMET platform proved to be a cost effective solution for multiple operations machining processes, typical in cast automotive parts, especially because

- high automation level breaks down the human labour costs and increases productivity rate
- geometrical tolerance are achieved with Configuration A, so this COMET solution is ready to be used in specific applications.

3.6.5 Outcome T5.3

Partner Gizelis tested COMET approach to machine a steel high precision component selected by partner Bazigos (see **Error! Reference source not found.**).
Goal of the demo was to machine comple*t*ely the part from the steel block, assessing the accuracy reachable with robot.
A Yaskawa Motoman robot cell has been used, with spindle hold by the robot. Configuration A and B (Kinematic model) have been set up. The full machining process has been successfully tested with Configuration A.
Main outcomes from demonstrations are the followings:

- Good accuracy (near specification)
- Process cost reduction respect to CNC mainly from lower equipment cost (slower cutting process due to reduced feed rate and material removal rate)
- Much Higher Flexibility and Larger Working Envelope

Figure 3.6-4 left: GIZELIS COMET cell; right: steel high precision part

Demonstration proved that COMET approach is already a working solution for all machining processes where a not extreme accuracy is required, especially for large scale parts. Synergy with CNC in a machining shop is possible (cheaper robots can be used for roughing operations).

3.6.6 Outcome T5.4

Partners BTU and IPA tested COMET approach to machine a resin and a steel mould selected by partner Nisaform (see **Error! Reference source not found.**). Goal of the demo was to fully machine the moulds from the material block.

A Kuka robot cell was used both at BTU and IPA, with robot holding the part. Configuration A and B were set up at BTU, Configuration D (HDCM) at IPA. Main outcomes from demonstrations are the followings:

- Accuracy reached with Configuration A (0.13mm) was quite good even if not still compliant with the strict specification for injection mouldings; Configuration D reached an accuracy of 80 µm but only when the HDCM works at best with no oscillations
- COMET Configuration A and B have cheaper process costs than CNC even when slower

Figure 3.6-5 left: BTU COMET cell; middle: steel injection mould part; right: IPA cell, with HDCM

COMET Configuration A demonstrated to be suitable for the roughing machining of steel moulds. It came out, both for machining the steel mould and the resin one, that the milling strategy need to be adapted to robot behaviour in order to reach a good accuracy (e.g. minimising axis changes of direction). HDCM needs further developments and cost optimization to have Configuration D ready for industry.

3.6.7 Outcome T5.5

Further developments needed to have COMET approach mature for commercialization have been analysed by the consortium members and shared. Situation is different for the various configurations. Configuration A is ready for market and the PSIR system will be commercialised by Delcam. As regarding Configuration B: a list of necessary developments has been identified both for the robot models calibration procedures and for the compensated path calculation codes.
As regarding Configuration C the main action needed is to get technical and commercial agreements with robot manufacturers in order to tackle the issue of the latencies introduced by the robot controllers in the real time feedback loop.
For Configuration D further development are also needed to integrate CPA and HDCM controller with standard robot controllers.
Both Configuration C and D need cost reduction actions for the HDCM and ATIR components.

3.6.8 Overall appreciation on demonstration results

COMET approach has been effectively tested in industry environment. Six demo cells (3 ABB, 2 Kuka, 1 Motoman) have been set up, all with Configuration A, 5 with Configuration B K model, 2 with Configuration B JB model, 2 with Configuration C, 1 with Configuration D.

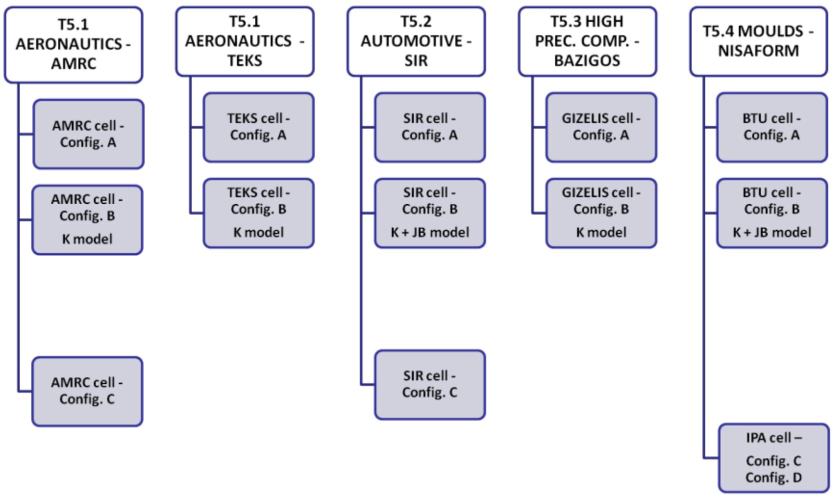


Figure 3.6-6 COMET configurations set up at Demo cells

Six industrial parts have been machined with COMET approach (2 Aluminium, 2 Steel, 1 Resin, 1 Inconel).

Results allowed concluding that:

- COMET Configuration A is ready to market; accuracy achieved is approximately +/-0.10 ÷ +/- 0.60 mm, compatible with using Robot for roughing machining (complimentary to an existing 5 Axis Machine tool, so increasing capacity by taking over the roughing operations).

- Configuration B, C and D are needed to gain finishing compliant accuracy, but they need further developments before using them in industry.
- COMET approach, especially for Configuration A and B is cost effective respect to CNC alternative.
- Main advantages pointed out by end users in using robots are flexibility (total automation, higher productivity, re- onfigurability) and large working envelope (CNC alternative equipment costs diverge with w.e.).

4 Impact via dissemination and exploitation

4.1 Impact

It is now clearer than ever that the revolutionary idea of COMET project is indeed a valuable technology know-how piece for the EU manufacturing. During the COMET seminars, the attendance volume in most of the events is showing that the field of robot machining is a problem solving platform for manufacturing, especially for the large volume operations. Moreover, during the machining experiments and simulation performed by the COMET partners, it has been proved that robot machining can speed up the roughing operation up to more than 200%, compared to the normally used CNC machines. It is finally calculated that at average 40% cost reduction is achieved by using the COMET platform, with minimal (if any) quality penalties. The 5 case studies as performed underline this statement like also the commercial interest as shown to several COMET partners by their customers

4.2 Dissemination

Already during the course of the project, it was seen as essential to disseminate the project outcomes to ensure a quick uptake by the European Manufacturing industry. The following dissemination activities were executed:

4.2.1 Task 6.2: Results of communication plan

Besides peer reviewed presentations/publications as described in T6.3 (4.2.2), publications for target audiences as described in T6.4 (T4.2.3), video footage as described in T6.5 (T4.2.4) numerous other dissemination activities have been executed. The following table includes all relevant information.

LIST OF DISSEMINATION ACTIVITIES							
NO.	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience
1	Presentations	Nikon	Info day - Exploit the opportunities for European research in the area of Nanotechnology, Materials and Production Technologies	1/6/2010	Belgium	Technology providers	N/A
2	Presentations	Delcam	Kick of COMET project	29/10/2010	Global	CAD/CAM/CAE stakeholders CNC stakeholders Aerospace manufacturing Robotics	N/A

3	Fair	Nisaform	Z-messe fair	20/4/2011	Germany	Manufacturing, Tool and Special-purpose Machinery Construction	N/A
4	Media Briefings	Delcam	Delcam European Press Conference	8/6/2011	Italy	European Journalists	N/A
5	Conference	BTU	ICPR conference	4/8/2011	Germany	Scientific Community Industry	N/A
6	Fair	Nikon	SAE AeroTech Congress and Exhibition	21/10/2011	France	Scientific Community Industry	N/A
7	Presentations	Delcam	COMET as a success story - PPP days	10/7/2012	Belgium	Scientific Community Industry Policy Makers Medias	N/A
8	Presentations	UPatras	Workshop on robot machining	5/4/2013	Germany	Scientific Community Industry	60
9	Presentations	IPA	Workshop on robot machining	5/4/2013	Germany	Scientific Community Industry	60
10	Presentations	BTU	Workshop on robot machining	5/4/2013	Germany	Scientific Community Industry	60
11	Fair	BTU	Hannover Messe	8/4/2013	Germany	Scientific Community Industry Policy Makers Medias	500.000
12	Conference	ULund	IEEE International Conference of Robotics and Automation	14/5/2012	USA	Scientific Community Industry	More than 200
13	Conference	ULund	10th IFAC Symposium on Robot Control – SYROCO 2012	5/9/2012	Croatia	Scientific Community Industry	More than 100
14	Conference	ULund	IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2011	25/9/2011	USA	Scientific Community Industry	More than 200
15	Conference	UPatras	45th CIRP Conference on Manufacturing Systems 2012	16/5/2012	Greece	Scientific Community Industry	More than 80
16	Conference	UPatras	7th International Conference on Digital Enterprise Technology	28/9/2011	Greece	Scientific Community Industry	More than 80
17	Conference	IPA	7th German	21/5/2012	Germany	Scientific	N/A

			Conference on Robotics			Community Industry	
18	Conference	BTU	21st International Conference on Production Research	31/7/2012	Germany	Scientific Community Industry	N/A
19	Conference	ULund	IEEE 17th Conference on Emerging Technologies & Factory Automation (ETFA), 2012	25/5/2011	Finland	Scientific Community Industry	N/A
20	Conference	BTU	7th International Conference on Digital Enterprise Technology	28/9/2011	Greece	Scientific Community Industry	More than 80
21	Fair	Delcam	Automatica Messe 2012	24/5/2012	Germany	Scientific Community Industry	500.000
22	Presentations	Delcam	Communicating EU research and innovation: A guide for project participant	24/10/2012	Europe	Scientific Community Policy Makers Medias	N/A
23	Video	SIR/Delcam	EU - Horizon 2020	3/5/2013	Europe	Scientific Community Policy Makers Medias	N/A

As originally scheduled in the beginning of the project, a significant amount of dissemination activities have been performed. These activities include project presentations, a number of press conferences and participation of COMET partners in Expo/Fairs. It is worth mentioning that COMET is an officially recognized EU project for the communication and dissemination strategy by featuring in the EU guide for " Communicating EU research and innovation: A guide for project participant ". Moreover the COMET project was selected and filmed for the promotional film, made by EC, on the Horizon 2020.

4.2.2 Task 6.3: Peer reviewed presentations / publications

The scientific and technical outcomes of the COMET project have been presented on and/or published in 14 conferences/journals. The following table provides the most important information for each publication.

LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS				
NO.	Title	Main author	Title of the periodical or the series	Date
1	*High-Accuracy Milling with Industrial Robots using a Piezo-Actuated High-Dynamic Compensation Mechanism*	*O. Sornmo*	*IEEE International Conference of Robotics and Automation*	*May 14, 2012*
2	*Increasing the Accuracy for a Piezo-Actuated Micro Manipulator for Industrial Robots using Model-Based Nonlinear Control*	*B. Olofsson*	*10th IFAC Symposium on Robot Control – SYROCO 2012*	*September 5, 2012*

3	Increasing Time-Efficiency and Accuracy of Robotic Machining Processes Using Model-Based Adaptive Force Control	O. Sornmo	10th IFAC Symposium on Robot Control – SYROCO 2012	September 5, 2012
4	Modelling and Control of a Piezo-Actuated High-Dynamic Compensation Mechanism for Industrial Robots	B. Olofsson	IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2011	Sept. 25, 2011
5	On an Empirical Investigation of the Structural Behavior of Robots	C. Doukas	45th CIRP Conference on Manufacturing Systems 2012	May 16, 2012
6	Präzisionsfräsen mit Industrierobotern	U. Berger	ZWF Zeitschrift fuer Wirtschaftlichen Fabrikbetrieb	Volume July-August, 2012
7	Machining with robots: A critical review	J. Pandremenos	7th International Conference on Digital Enterprise Technology	September 28, 2011
8	Programming System for Efficient Use of Industrial Robots for Deburring in SME Environments	T. Dietz	7th German Conference on Robotics	May 21, 2012
9	Reconfigurable strategies for manufacturing setup to confront mass customization challenges	S. Minhas	21st International Conference on Production Research	July 31, 2011
10	Milling with industrial robots: Strategies to reduce and compensate process force induced accuracy influences	C. Lehmann	IEEE 17th Conference on Emerging Technologies & Factory Automation (ETFA), 2012	Sept. 17, 2012
11	On the integration of skilled robot motions for productivity in manufacturing	A. Björkelund	IEEE International Symposium on Assembly and Manufacturing (ISAM), 2011	May 25, 2011
12	A multilevel reconfiguration concept to enable versatile production on distributed manufacturing	S. Minhas	7th International Conference on Digital Enterprise Technology	September 28, 2011
13	Compensation of Errors in Robot Machining With a Parallel 3D-Piezo Compensation Mechanism	U. Schneider	46th CIRP Conference on Manufacturing Systems 2013	May 29, 2013
14	Robot Joint Modelling and Parameter Identication Using the Clamping Method	C. Lehmann	IFAC Conference on Manufacturing Modelling, Management and Control	June 19, 2013
15	Machining with industrial robots: the COMET project approach	C. Lehmann	International Conference Flexible Automation and Intelligent Manufacturing 2013	June 26, 2013
16	Offline Path Compensation to Improve Accuracy of Industrial Robots for Machining Applications	C. Lehmann	Automation 2013	June 25, 2013

A large number of scientific publications have been prepared and published on the research work performed during the course of the COMET project. In more details 16 papers have been published till the time that this report was prepared, with another one already accepted and to be published till the end of. Finally, it has to be mentioned that except Europe, two of COMET papers have been presented in USA by COMET partners.

4.2.3 Task 6.4: Publications for the targeted audiences

During the course of the project, more than 40 press releases and articles of the project objectives and intermediate outcomes have be written and disseminated amongst the targeted audiences to update these audiences on the project progress. The following table provide all the relevant information of the actual publications.

LIST OF PRESS RELEASES AND ARTICLES						
NO.	Type of activities	Main leader	Title	Date	Type of audience	Size of audience
1	Press Releases	Delcam	European "COMET" Project targets the use of industrial robots for high-end machining for cost effective, flexible and reliable manufacturing solutions in the 'Factory of the Future'.	1 October 2010	Scientific Community Industry Medias	More than 1000
2	Press Releases	Delcam	COMET Project Familiarisation Training Success	1 December 2010	Scientific Community Industry Medias	More than 1000
3	Press Releases	Delcam	COMET Project Partners Discuss Robot Manufacturing Solutions with the European Commission	1 April 2011	Scientific Community Industry Medias	More than 1000
4	Press Releases	Delcam	COMET Project Focuses on New Robot Manufacturing Solutions	1 October 2011	Scientific Community Industry Medias	More than 1000
5	Press Releases	Delcam	COMET robot machining consortium meets at Fraunhofer	24-25 November 2011	Scientific Community Industry Medias	More than 1000
6	Press Releases	Delcam	COMET Project Discuss Innovative Robot Machining Developments	April 2012	Scientific Community Industry Medias	More than 1000
7	Press Releases	Delcam	COMET Project Shapes the Future of Robot Machining	11-13 April 2012	Scientific Community Industry Medias	More than 1000
8	Press Releases	Delcam	COMET Project on its trajectory towards success	26-28 September 2012	Scientific Community Industry Medias	More than 1000
9	Press Releases	Delcam	R&D Work Finalised	11-12 December 2012	Scientific Community Industry Medias	More than 1000

10	Press Releases	Nisaform	COMET Project Partner NISAFORM at Z-Messe	April 2011	Scientific Community Industry Medias	More than 1000
11	Press Releases	Delcam	Delcam host successful UK Technical Seminar	25 April 2013	Scientific Community Industry Medias	More than 1000
12	Articles published in the popular press	TEKs	Exploring robotics for the factory of the future	June 2011	Scientific Community Industry Medias	N/A
13	Press Releases	Delcam	COMET Technologies: Programming and Simulation Environment for Industrial Robots	June 2011	Scientific Community Industry Medias	More than 1000
14	Articles published in the popular press	IPA	Spanende Bearbeitung mit Industrierobotern	June 2011	Scientific Community Industry Medias	N/A
15	Articles published in the popular press	Delcam	Produrre velocementee meglio	July 2011	Scientific Community Industry Medias	N/A
16	Articles published in the popular press	Delcam	Delcam - recent and forthcoming developments in overview	July 2011	Scientific Community Industry Medias	N/A
17	Press Releases	Nikon	COMET consortium member Nikon Metrology helps transform industrial robots into precision machine tools	July 2011	Scientific Community Industry Medias	N/A
18	Articles published in the popular press	Delcam	Software-ontwikkelingen bij Delcam	August 2011	Scientific Community Industry Medias	N/A
19	Articles published in the popular press	Delcam	Integrazione, interoperabilita, personalizzazione	August 2011	Scientific Community Industry Medias	N/A
20	Articles published in the popular press	SIR	Robot per la meccanica di precisione?	August 2011	Scientific Community Industry Medias	N/A
21	Articles published in the popular press	Delcam	Le nuove frontiere del CAD/CAM	August 2011	Scientific Community Industry Medias	N/A
22	Articles published in	Delcam	Europejska konferncja prasowa Delcam	September 2011	Scientific Community	N/A

	the popular press				Industry Medias	
23	Articles published in the popular press	Delcam	Minder omspannen dankzij adaptief frezen	September 2011	Scientific Community Industry Medias	N/A
24	Articles published in the popular press	SIR	Tutt i insieme nel nome Delcam	September 2011	Scientific Community Industry Medias	N/A
25	Articles published in the popular press	Delcam	Insieme progettazione e reverse engineering	October 2011	Scientific Community Industry Medias	N/A
26	Articles published in the popular press	Delcam	De toekomst van verspanen: robots!	November 2011	Scientific Community Industry Medias	N/A
27	Articles published in the popular press	-	Robots as Precision Machine Tools	March 2012	Scientific Community Industry Medias	More than 21.000
28	Articles published in the popular press	TEKs	Exploring Robotics for the Factory of the Future	January 2012	Scientific Community Industry Medias	N/A
29	Articles published in the popular press	Delcam	Robot Machining	April 2012	Scientific Community Industry Medias	N/A
30	Articles published in the popular press	TEKs	Project looks to develop robots for precise machine milling	25 April 2012	Scientific Community Industry Medias	N/A
31	Articles published in the popular press	Bazigos	Goals & Bazigos SA Participation	June 2012	Scientific Community Industry Medias	More than 5000
32	Articles published in the popular press	TEKs	TEKS – Reaching beyond the COMET	May 2012	Scientific Community Industry Medias	N/A
33	Articles published in the popular press	Nikon	Factories of the future [deel 1]: COMET optimaliseert robotbeweging	May 2012	Scientific Community Industry Medias	N/A
34	Articles published in the popular press	Gizelis	Results of Gizelis' new Motoman cell	December 2012	Scientific Community Industry Medias	More than 3000

35	Articles published in the popular press	SIR	Factories of the future: Beyond the limits of Industrial Robotics	October 2011	Scientific Community Industry Medias	N/A
36	Press Releases	TEKs	Dual purpose setup of the TEKS robot cell	October 2011	Scientific Community Industry Medias	N/A
37	Articles published in the popular press	Gizelis	Robots change the industrial future replacing the CNC machines	October 2011	Scientific Community Industry Medias	More than 3000
38	Articles published in the popular press	TEKs	Solving the challenges of robot machining	October 2011	Scientific Community Industry Medias	More than 3000
39	Articles published in the popular press	AMRC	COMET Technologies in the Aerospace Industry	October 2011	Scientific Community Industry Medias	More than 3000
40	Press Releases	ARTIS	First metal cut at TEKS monitored with 500 kHz	March 2011	Scientific Community Industry Medias	N/A
41	Articles published in the popular press	Nisaform	Strojarstvo Trojirenstvi	September 2011	Scientific Community Industry Medias	N/A
42	Press Releases	Gizelis	Anouncing COMET seminars	February 2013	Scientific Community Industry Medias	>5000
43	Articles published in the popular press	Nikon	FoF-project 'COMET' ontwikkelt industriële robots voor precisieverspaning	8 February 2013	Scientific Community Industry Medias	
44	Articles published in the popular press	AML	AMRC spin-off expanding	November 2012	Scientific Community Industry Medias	N/A

A large number of publications and press releases for the generic audience (more than 40) have been prepared and published on various magazines, online portals and technical bulletins. It is worth mentioning that all partners have published an article at least once, even though some partners are not officially involved in this task (T6.4). Due to the nature of publications, it was not viable to report the actual size of the audience reached, but where possible, an indicative number is provided.

4.2.4 Task 6.5: Videos showing project results

During the course of the project, the COMET consortium has released several videos on the project development and results. All these videos have been stored on and made available via the Consortium website (http://www.cometproject.eu/media-videos.asp) and via the Consortium YouTube channel (http://www.youtube.com/user/COMETproject). The following table list all the COMET videos.

LIST OF VIDEO'S					
NO.	Main leader	Title	Date	Place	Audience (video views)
1	Delcam, AML, TEKs	Advanced Robot Machining with the COMET Project	18 Jan 2011	Sheffield, UK	2.110
2	Delcam, Frauhofer IPA	COMET Project Update - The Future of Robot Machining	27 Feb 2012	Stuttgart, Germany	372
3	Delcam	Project Coordinator Jan Willem Gunnink, Delcam, speaks about COMET as a success story	23 Jul 2012	Brussels, Belgium	246
4	Delcam, ULund	COMET Project Update – Offline compensation	3 Jul 2012	Lund, Sweeden	235
5	SiR Spa	Programming and Simulation environment for Industrial Robots (PSIR)	16 May 2011	Modena, Italy	370
6	SiR Spa	Adaptive Tracking System for Industrial Robots (ATIR)	16 May 2011	Modena, Italy	141
7	SiR Spa	High Dynamic Compensation Mechanism (HDCM)	16 May 2011	Modena, Italy	225
8	SiR Spa	Aluminium machining test at SIR SpA	19 May 2011	Modena, Italy	742
9	SiR Spa	Aluminium machining test at SIR SpA	4 Jul 2011	Modena, Italy	245
10	SiR Spa	Aluminium machining test at SIR SpA	4 Jul 2011	Modena, Italy	462
11	TEKs	COMET project demonstration: Advanced Robot Machining Simulation with the COMET project: Teks	2 May 2013	Sheffield, UK	12
12	SiR Spa	COMET project demonstration: Advanced Robot Machining Simulation with the COMET project: SiR	9 Jan 2013	Modena, Italy	118
13	Gizelis Robotics, UPatras, Delcam	COMET Project - Gizelis Robotics machining hard steel	30 April 2013	Schimatari, Greece	1.976
14	BTU	COMET Project - BTU Cottbus machining food bowl mould	1 May 2013	Cottbus, Germany	14
15	TEKS, UPatras	COMET project - TEKS cell Demonstration	4 Jan 2011	Sheffield, UK	215
16	Frauhofer IPA	COMET Project - Fraunhofer IPA: HDCM demonstration	3 Feb 2013	Stuttgart, Germany	25

Originally a number of DVDs was foreseen to be prepared and distributed amongst the targeted audiences to make them aware of the new possibilities this EC funded project has provided. The COMET consortium is filming most of the machining trials and other significant events, such as General Assembly meetings and important dissemination events. Moreover a number of simulation and “concept” videos have been prepared, in order to visualize the COMET platform from the early stage of the R&D tasks. All those videos (a total of 16 videos) have been professionally edited and uploaded in the best possible quality in the purpose created COMET YouTube channel, where all the videos are available to the general public. Already, more than 5000 views have been achieved and audience located in more than 50 countries has been reached.

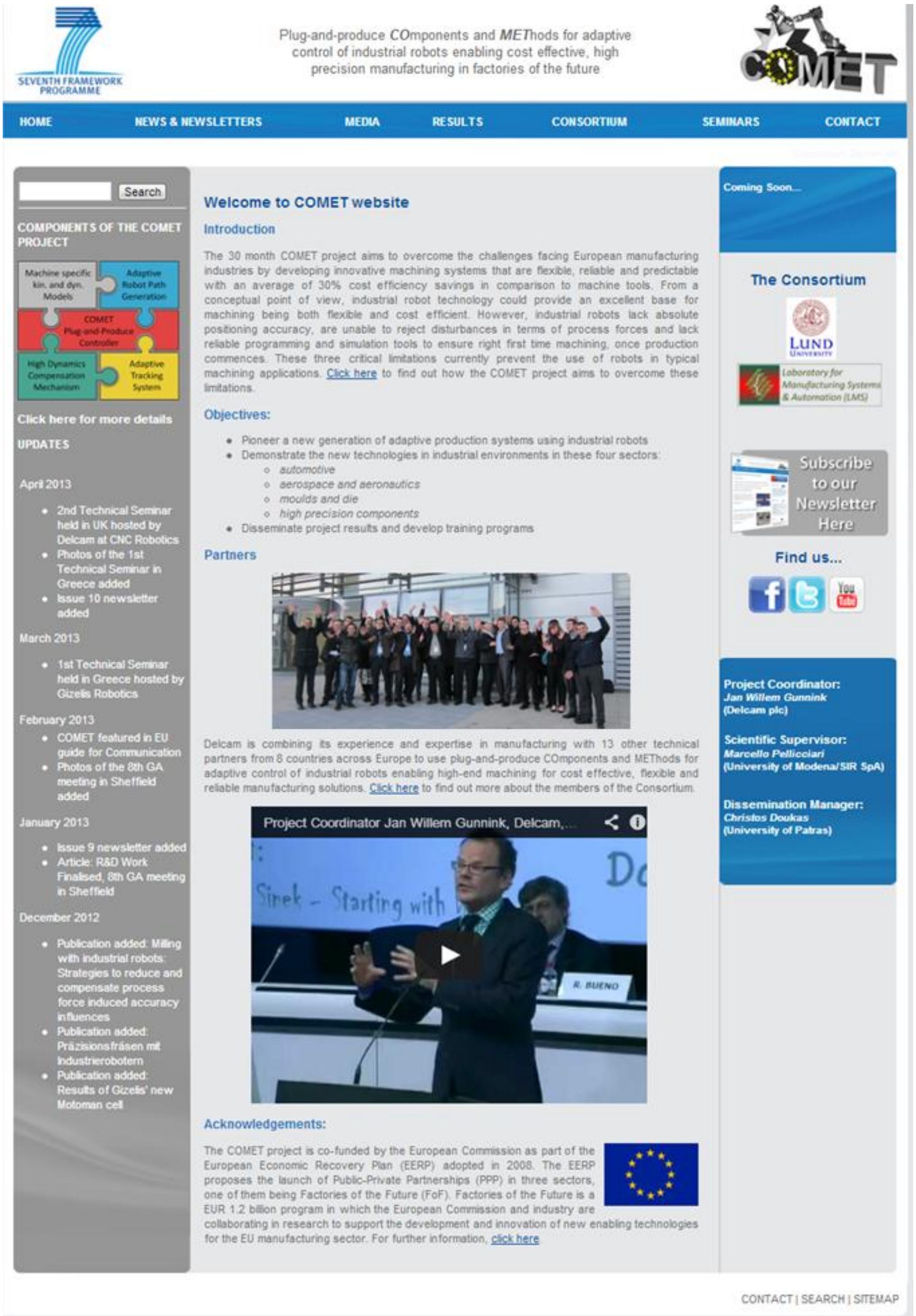
4.3 Exploitation

During the course of the project, 13 exploitable results have been identified. In addition to those results, one patent application is pending based on the content of one of the results. Finally a spin-off company called Cognibotics AB, founded by COMET partner ULund, gis oing to offer services based on the COMET results. Further details however can’t be given due to the confidential nature of this information.

5 Website and contact details

Detailed information on the project outcomes and further details can be found on:

www.cometproject.eu



6 Acknowledgement

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