REAL-TIME 7DOF POSE CONTROL OF AN INDUSTRIAL ROBOTIC SYSTEM FOR MACHINING OF LARGE-SCALE CFRP PARTS IN THE AEROSPACE INDUSTRY

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INTRODUCTION
The Automation and Production Technology department at the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (IFAM) in Stade, Germany, has been an established partner of CFK NORD for many years and does research in the field of automation technology, especially with regard to the integration of industrial robot technology in machining and assembly processes for aircraft production. At Fraunhofer IFAM, integrated system solutions and plant concepts are worked out and can be implemented and optimised on a one-to-one scale in a 4000 square metre test hall with a height of 15 metres below crane hook. This allows for the development of solutions from a single source that can then be transferred to large-scale applications without unnecessary delay and with minimal expenditure, therefore securing a lead in delivering innovative new technologies.

Zero defect production is especially required when machining parts at key points of the production process, and this is only achievable through definite process control. An important tool thereafter is error prevention through the monitoring of quality-determining process parameters. Milling, drilling and water-jet cutting are focus areas in the process development field. The researchers at Fraunhofer IFAM, in cooperation with the Hamburg University of Technology (TUHH), integrate industrial robots or portal machines within processes that simultaneously require both high precision and high mobility of the tool along the work piece. Moreover, they prepare solutions for the simultaneous engagement of several machining units on the same work piece.

There is high demand for the efficient machining of large structures in the aircraft industry in order to reduce lead times, and this has driven increased usage of industrial robots as an alternative to currently installed specialist machines. A major drawback of industrial robots within the application of machining is the insufficient absolute accuracy caused by their serial structure, the resilience of gears and external influences such as temperature fluctuations. Besides this, the high machining forces that occur during the machining of carbon-fibre reinforced polymer (CFRP) components in the aircraft industry lead to significant deviations of the tool center point (TCP) from its target path because of the low stiffness of the robot kinematic. These deviations cannot be measured with the help of internal rotary encoders at the motors and therefore cannot be affected or compensated for by calibration routines and the internal robot controller.

This whitepaper demonstrates an opportunity to improve the accuracy of an industrial milling robot during the milling process with the help of a Leica Absolute Tracker AT960 used as an external measurement system. In order to detect the position and orientation of the TCP of the milling tool while processing, a Leica T-Mac probe is mounted on the spindle to allow for 6DoF measurement. The pose data of the end effector is transmitted to the CNC-based machine controller of the robot in milliseconds through the real-time EtherCAT bus system, which calculates the path correction. Apart from the 6DoF pose information, this data contains highly precise time measurements, so that it can be denoted as a 7DoF measurement. The introduction of an additional controller cascade in the CNC-controller of the robot enables precise path correction in real-time, so that the geometry of the milled path meets the challenging tolerances of the aircraft industry.
TECHNOLOGY DESCRIPTION OF LASER TRACKER
The expertise of Hexagon Manufacturing Intelligence is in providing and supporting sensing, thinking and acting solutions for industrial manufacturers. The next-level industry trend for bringing quality control inline within production processes requires the innovative evolution of industry proven sensors. In large-volume production applications such as aerospace assembly, Leica Absolute Tracker systems measure distance and horizontal and vertical angle to a spherical mounted reflector, delivering precise 3DoF measurements 1000 times per second. The Absolute Interferometer (AIFM) ensures a distance lock-on accuracy of as little as ±10 microns over the full working range of the system, even on moving targets.

By combining conventional laser tracker measurements with photogrammetry, the integrated mini-variozoom camera of the Leica Absolute Tracker AT960 additionally determines roll, pitch and yaw angle on LED-equipped probes such as the Leica T-Mac. This allows the system to deliver precise 6DoF positioning and orientation information with accurate time stamps. For traditional tasks such as part inspection this data runs through the LMF interface, while 7DoF metrology-assisted manufacturing is supported by the addition of the real-time industrial Ethernet feature pack based on the EtherCAT standard.

SYSTEM DESCRIPTION
A robot cell for machining of large structures was used for the experiments at Fraunhofer IFAM (see Figure 1).

To ensure maximal compatibility, the robot is equipped with a Siemens SINUMERIK 840D sl CNC-controller. This controller is particularly common for five-axis milling machines and offers a number of interfaces for different applications.

For the application described here, the controller offers the possibility to execute appropriate C++ code, which is executed in each control cycle at run time. Correction signals at the joints enable the robot to execute the corrected path. This interface is called the Universal Compensation Interface (UCI), with the associated software application UCI-App (see Figure 2).

Currently, robotics mainly uses cascaded control concepts on individual axes. These consist of a position control loop and internal speed and current control loops including pose- and load-dependent moments and speed pre-control. The internal cascades work with shorter cycle times than the position control loop, whose cycle-time usually lies between 4 and 12 milliseconds. The control parameters are configured in such a way that the control loop remains stable across the entire workspace and for diverse loading conditions and paths of motion. Since the axes of the robot are mechanically fixed and because cross coupling can be understood as a multivariable system, the direct approximation of the six individual single-in single-out controls makes a very robust controller design necessary. Model-error limited deviations are therefore seen and compensated for as external perturbations.

The laser tracker control loop extends this concept of an external cascade, consisting of 7DoF laser tracker measurements, the kinematic robot model and the actual controller – the UCI-Control. In order to proceed with the approximation of six independent, single-axis-based controls, this additional control also takes place on the axis base. It is converted to the joint errors with help of TCP pose errors measured considering the inverse-kinematic model by the AT960. These joint errors are added as compensation values to the robot path planning by the UCI-Control and lead to highly precise operation of the robot.

In case of pure 3DoF control, this approximation is not directly applicable, since the measurements of three coordinates do not suffice to calculate six single-joint angles. In this case, the control takes place in Cartesian space and a 3D-correction vector will be returned to the robot controller. These measurements are transferred with a very small latency and a highly accurate time stamp. For clarity, this control type will be from here on referred as 3DoF control.
In order to transfer data between the AT960 and the robot controller, various real-time bus systems will be deployed. The AT960 uses EtherCAT to provide pose and position data as well as the time stamp in real-time, whereas the SINUMERIK 840D sl works on the basis of Profinet IRT (Figure 3). The synchronisation between EtherCAT- and Profinet IRT-cycles takes place in a gateway, which converts the bus protocols. This factor complicates the deterministic triggering and usage of a measurement process, and can be avoided by the application of a trigger signal based on RS422.

For that purpose, the UCI-App sends a precise trigger signal to the AT960 controller in every CNC-clock cycle and saves the corresponding time stamp. With the confirmation of trigger signal receipt, the AT960 sends the actual position or pose data and the time stamp via EtherCAT to an industrial PC, which in serving as the EtherCAT-Master forwards the data to the CNC-control via the gateway. The UCI-App compares the time stamp of the trigger and the received pose data packets and relates the corresponding data. Thus, a data transfer between EtherCAT and Profinet IRT including time critical measurement resolution is realised.

The test setup for robot absolute accuracy determination replicates a milling process of a large structured component (Figure 4). Three vertical planes are approached in a nine-by-nine point pattern, which is positioned in a S° component system. The robot stops at each of the points for several seconds until the possible vibrations fade away so that measurement data can be correctly collected. During this time, the robot is steady with respect to the external laser tracker controller.

The absolute accuracy will be measured in three trial passes: without external control; with 3DoF control; and with 6DoF control. The AT960 measures the Leica T-Mac for pose control and Reflector 1 for a 3DoF control (see Figure 5). The absolute position is determined directly at the TCP via Reflector 2 through an independent, dynamic Leica Absolute Tracker in the same reference coordinate system.

The measured values without control show the absolute accuracy of the robot itself, which can clearly be improved by either 3DoF or 6DoF control. It is to be noted that the results of 6DoF control are superior to 3DoF control. The remaining errors of the 3DoF control can be traced back
largely to the inferior control strategy and remaining initial measurement errors between the work piece and the robot, as well as orientation errors that arise at the TCP due to the consideration of leverage effects as position errors. The latter will be considerable in this respect, since during production the visibility of the space near to the TCP-mounted reflector can be limited due to the possible chip emission and the complicated geometry of the component. A longer distance between the reflector and the TCP will have a longer lever arm and result in equivalently larger position errors of the TCP.

TENSILE FORCE TESTS
The strength of the external controller is best demonstrated when the robot is impacted by external effects that are not measured with the internal encoders of the motors. Among these are expansion and contraction effects in the structure due to heating of the motors and structures, or external force impacts, for example process forces.

External forces operate on both the structure and the gears of the robot. Depending on the direction of the effect, these forces vary the resultant position error. In addition, during the milling process strong fluctuating process forces can arise so that a previously calculated compensation or modelling becomes very complicated. In order to simulate especially the milling cutter’s entry and exit paths and the forces arising due to them, a setup as shown in Figure 7 is chosen.

In the experiment, a constant force orthogonal to the direction of movement is applied with the help of weights at a constant feed rate. These forces divert the robot from its planned path due to its structural composition. At time t1, the weight is abruptly removed. This results in a sudden step of force, which excites the natural frequencies of the system. It is then expected that the robot will move on the target path with regard to path accuracy.

The result is a path error of 0.5 millimetres if external control is disabled. After removal of the weights, the robot follows its path as expected. When the 6DoF control is used, the strength of this controlling concept can be observed. The 6DoF control resists any kind of effect from the weight prior to the force step and leads the robot back to its planned path afterwards. Since the control dynamic and amplification of the internal cascade cannot be influenced through the UCI-App, one can in this case identify the limits of the controller. High dynamic external stimulation, especially in range of the first resonant frequency of the robot, can hardly be prevented. Only the increment of the controller bandwidth of the state and speed of the internal cascade can bring improvements at this place, from which an external control loop would benefit equally. In other words, this means that the error can be compensated, as long as the bandwidth of the occurring disturbing forces is smaller than the bandwidth of the external laser tracker control loop.

Altogether, these measurements show that, as far as the external operating forces are static or having low frequency, deviations can be successfully prevented from the planned path with the help of 6DoF control. Since typical temperature changes have low frequency behaviour, temperature influences can also be expected to be adjusted using a 6DoF control.

MILLING TEST
The suitability of the external control for accuracy improvement in machining processes is validated by the milling test below. The milling tests were carried out in the polyurethane material NECURON® 1007, which is normally used for modelling or in-forming. Because of its homogeneous structure, it is very suitable for milling tests, as the milling forces can be kept constant and scale by changing machining parameters. In order to produce strong machining forces, a tool with a diameter of 15 millimetres, three cutting edges and a
feed rate of 2500 millimetres-per-minute turning at a rate of 6000 RPM was used.

For every experiment, two parallel notches were milled in opposite directions. This leads to normal forces which point at each other and reduce the width of the remaining bar between the notches. The width of the bars can be verified with the help of simple measurements to determine the deflection from the planned path during the milling process. Besides, the actual path of the TCP of the robot is recorded with the help of the second tracker. In order to avoid high-frequency stimulation during the process, a very small acceleration was chosen, which leads to a constant rising speed and equivalent normal forces (see Figure 9).

![Figure 9: Deflection during milling process due to normal force effects, measured with additional Leica Absolute Tracker](image)

The desired bar width between the slots should be three millimetres. As seen, the path is followed with the help of the 6DoF control while the robot deviates from its target path without external control.

These results confirm the observations of the previous experiment with external tensile forces. It is possible to obtain the straight-milled path within the range of the robot path repeatability with the help of an external laser tracker support system. This way, a significant quality improvement benefit is realised in the machining of large components.
CONCLUSION AND SUMMARY

In 2015, about 1200 new aircrafts were commissioned at Airbus. Together with previous orders, Airbus has to deliver about 7000 aircrafts in the next year as demand is growing constantly, especially for medium-sized aircrafts. With the limited production capacity in the manufacturing plants of the aircraft industry, the demand for automation is increasing rapidly. The replacement of large portal machines and the shift towards flexible production in the sense of the “Factory of the Future” promotes the demand for novel plant concepts and solutions. Fraunhofer IFAM, together with Hexagon Manufacturing Intelligence, has demonstrated how high-precision manufacturing might appear in the future, making use of external 6DoF control on an industrial milling robot.

The demonstrated solution includes a complete integration and fusion of 7DoF measurement technology and machine control in an encapsulated real-time environment with direct access to measurement and control data. The integration of an external control loop enables improvements in the pose accuracy of the robot up to the range of the repeatability of the kinematics. Particularly in the aerospace industry, whose focus is on low tolerances for drilling and milling processes, while at the same time dealing with large structural dimensions, the overall system design shown here is very clearly applicable. In combination with mobile moving platforms, the highly precise workspace of the robot system – even without complete calibration of the robot – can be compared with the working range of large machine tools and, in return, saves high investment costs for heavy load foundations and special systems. The results presented here show that the integration of a real-time laser tracker into an adaptive milling robot cell is a highly efficient alternative for the automated processing of large components in the factories of the future.
Hexagon Manufacturing Intelligence helps industrial manufacturers develop the disruptive technologies of today and the life-changing products of tomorrow. As a leading metrology and manufacturing solution specialist, our expertise in sensing, thinking and acting – the collection, analysis and active use of measurement data – gives our customers the confidence to increase production speed and accelerate productivity while enhancing product quality.

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