

Real Time Pose Control of an Industrial Robotic System for Machining of Large Scale Components in Aerospace Industry Using Laser Tracker System

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ABSTRACT

The high demand of efficient large scale machining operations by concurrently decreasing operating time and costs has led to an increasing usage of industrial robots in contrast to large scaled machining centers. The main disadvantage of industrial robots used for machining processes is their poor absolute accuracy, caused by the serial construction, resilience of gears and sensitivity for temperature changes. Additionally high process forces that occur during machining of CFRP structures in aerospace industry lead to significant path errors due to low structural stiffness of the robot kinematic. These errors cannot be detected by means of motor encoders. That is why calibration processes and internal control laws have no effect on errors caused by elastic deformation. In this research paper an approach for increasing the absolute accuracy of an industrial milling robot with help of a Laser Tracker system during machining tasks will be presented. To measure the position and orientation of the robot tool center point (TCP) a specific adapter is mounted on the milling spindle near the TCP to provide a 6DoF measurement. Via a real time interface pose data can be obtained in millisecond cycles and is used for calculating the current path errors of the robot. The implementation of an additional controller in the manufacturers CNC allows the correction of the programmed trajectory so that the machining path will match its specifications.

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INTRODUCTION

In 2015 approximately 1200 new aircrafts have been ordered at manufacturer Airbus [1]. Combined with previous orders, Airbus has to deliver 7000 aircrafts in the next years, while demand - especially for single-aisle aircrafts is steadily growing [2]. While plant capacity limits are almost reached, this ongoing market growth in aerospace industry leads to high demands in automation processes. Today large gantry machining centers are used to perform drilling and milling operations [3]. Therefore the machining centers need to be bigger than the actual workpiece which requires heavy duty fundaments to absorb the enormous loads of the portals (up to 40 tons). To increase aircraft production rate, different approaches are viable. One of the possibilities is the application of industrial robots [4]. This paper shows one way to increase efficiency in manufacturing processes by using an external guided industrial robot as a milling machine. Mobilizing this robot via mobile platforms opens up the workspace without limitation and ensures accessibility of large scale components [5],[6]. One downside of 6-axes articulated robots is their poor absolute accuracy and structural stiffness compared to machining

centers [7]. To overcome this disadvantage the approach presented here shows a way to improve the absolute accuracy of an industrial robot with help of external measurements performed by a highly dynamic Laser Tracker system with real time interface. The concept of external guidance has already been shown in different works [8, 9, 10, 11]. However, the utilization of real time bus systems as well as direct input and intervention in the robot control represents a novel approach. On the one hand the Laser Tracker system is used to calibrate pose relationships between the workpiece, the robot and itself as well as the pose relationship between the robot Flange and the milling tool. The calibrations and algorithms developed in this work demonstrate a precise way to calculate the absolute pose of the robot TCP with respect to the workpiece with help of the Laser Tracker system. That way the Laser Tracker is able to measure the actual position of the robot and along with the intended target position from the robot control the pose error can be detected. Additionally this paper displays a feedback loop to feed back the

error to the robot control to eliminate the robot absolute pose error in real time. A 3DoF feedback loop is discussed as well as a 6DoF feedback loop.

PLANT LAYOUT AND TEST ENVIRONMENT

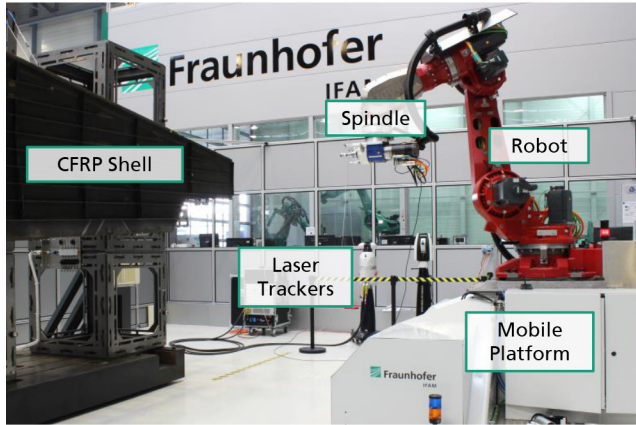


Figure 1. Mobile robotic system for machining applications

The current setup was build up during the project *ProsihP II*¹ which consists of a CNC controlled industrial robot - based on the *Max 150* by *MABI Robotic* - mounted on a self-driven platform. The platform is capable of moving in any direction and is equipped with all necessary accessories for machining - such as supply for the milling spindle, dust removal systems and process force detection systems. To calibrate the desired transformations and to measure the TCP-pose, multiple sphere mounted retroreflectors called *Red Ring Reflectors* are placed at the robot end effector. The following subchapters will describe the overall setup more in detail.

CNC Controlled Industrial Robot

To achieve maximum compatibility, the robot is equipped and controlled by a *Siemens Sinumerik 840D sl*-CNC control. This control is widely spread in all kind of CNC machines such as multi axes milling machines or turning centers from large manufactures [12] and offers a wide range of interfaces for all kind of applications. The actual CNC kernel works with standard G-Code commands and thus allows handling the robot like every other CNC-based machine. Most importantly this control provides the possibility for end users to execute own software in C++-code, that can manipulate the robot axes angles in real time. This interface is named *Universal Compensation Interface* (UCI) whereas the user software is called UCI-App. This app is essential for feeding the calculated correction values from the external Laser Tracker into the internal robot control cycle as an additional cascade.

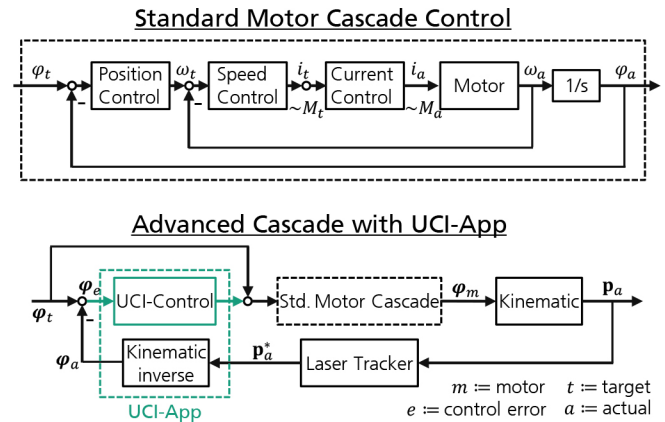


Figure 2. Cascade control and advanced control with UCI-App

The actual control law and the control structure of the UCI-Control will be presented separately later on. The UCI-App provides access to process data and parameters during operation. The control operates with an 8 millisecond interpolation cycle while the speed and current control work in 1 ms and 125 μ s cycles. For a well-working control loop it is important to note, that the measuring system (in this case the Laser Tracker) should at least have the same or higher measuring rates, so that the control gets new data in every cycle.

The industrial robot kinematic reaches up to 2.2 m, has a load capacity of 150 kg and is equipped with both motor encoder systems and secondary encoders on every axis that are capable of providing direct angle measurements without any effects of gearings and bearings. However due to comparability to usual industrial robots the secondary encoders have not been used in the present tests.

Laser Tracker System and Real Time Interface

The Laser Tracker used for the control shown in Figure 2 is a *Leica Absolute Tracker AT960-XR* [13] which provides dynamic six degrees of freedom (6DoF) measurements up to 100 Hz. To measure 6DoF with a Laser Tracker the addition of the measuring probe *Leica T-Mac* is required. The probe is equipped with several infrared LEDs that will be tracked by a camera which is integrated into the Laser Tracker [14]. Thus the orientation is added to the highly accurate position measurement. For 3DoF measurements a simple spherically mounted *Retro-Reflector* is sufficient and up to 1000 Hz sampling rate is possible. The *maximum permissible error* (MPE) is specified as $15 \mu\text{m} + 6 \mu\text{m/m}$, which means that the overall accuracy of the Laser Tracker diminishes over distance [15]. Therefore it is important to install the tracker in immediate environment to the robot to prevent further uncertainties and errors. Additionally a *Leica Absolute Tracker AT901* is used for monitoring the path and positioning results during the tests.

To transfer data between Laser Tracker controller and robot control different bus systems are utilized. The Laser Tracker system uses *EtherCAT* to provide pose and position data as well as time stamps while the *Sinumerik 840D sl* utilizes *ProfiNet IRT*. Figure 3 shows the signal flow chart of the present architecture. The *EtherCAT* and *ProfiNet IRT* bus segments are linked via a Gateway which transfers data with the drawback of a short delay.

1. ProsihP II: "Prozesssichere hochproduktive Präzisionsbearbeitung von CFK Großstrukturen", LuFo Niedersachsen: ZW 3-80140004

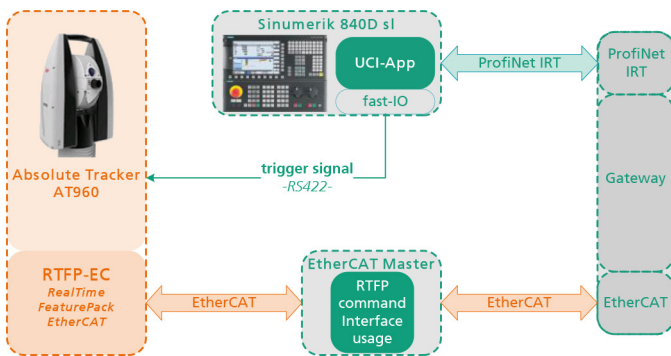


Figure 3. Signal flow chart of used real time interfaces and bus systems

In every CNC cycle of 8 ms the UCI-App sends a temporal high-precision trigger signal to the Laser Tracker. With receipt of the trigger the laser tracker sends pose/position and timestamp data via *EtherCAT* to an industrial Master PC that forwards the data via Gateway to the CNC control. The cost is at least one missed cycle which is not germane for the overall pose correction².

End Effector Design

The robot end effector consists of a milling spindle *SLQ120* with HSK interface, which is used for milling and drilling operations of CFRP components. The HSK interface allows quick and precise exchange of different tools. To get most realistic impressions of accuracy during milling operations, a special tool including a magnetic nest to hold reflectors is measured and utilized in all tests that do not imply direct milling operations. This TCP is surveyed during the tests by the AT901 Laser Tracker. For milling operations with the 3DoF control another reflector mount is necessary. Because orientational errors - that occur as positional errors at the TCP - will not be captured by the UCI-control, it is necessary to place this reflector as near as possible to the TCP.

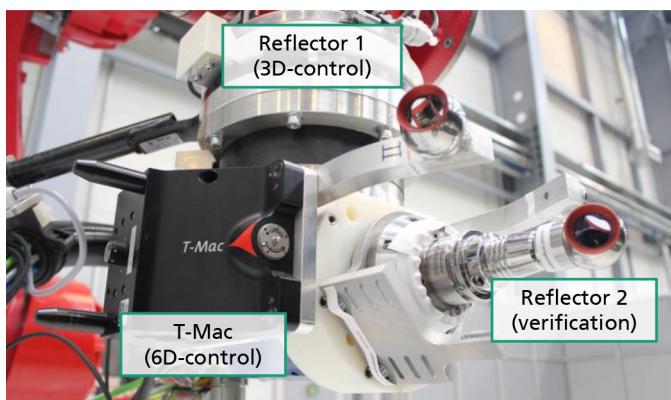


Figure 4. End effector design with different measurement options

Figure 4 shows this setup. For the 6DoF-control the earlier mentioned measuring probe *T-Mac* is mounted on one side of the spindle. In contrast to reflector balls the face of the *T-Mac* is fixed, which constitutes a major limitation in terms of flexibility and visibility for the 6DoF control. Although the reflector balls can be turned for static

usage, this challenge also applies to the 3DoF-control. However, special reflectors like *Cat-Eyes* or new developments with significantly increased aperture angles can master this challenge.

CONTROL STRATEGY

The industrial robot arm, controlled by a Siemens Sinumerik 840D sl, has independent controllers for each axis. Some components of the control algorithms run on the same piece of hardware but from theoretical point of view for each axis there is one closed loop control. The common and robust cascade structure is used for the control loops. To obtain high path accuracy, feedforward control is used. Additionally, the controller uses a mathematical model of the robot dynamics to adapt the control parameters depending on the current robot pose.

In general, from the control theory point of view, robot arms are nonlinear “multiple input, multiple output (MIMO)”-systems. For example, acceleration of a main axis can lead to torques on other axes, they are “coupled”. When the manufacturer applies independent controllers to each axis, the robot is assumed to be a set of six independent linear “single input, single output (SISO)”-systems. This assumption is often fulfilled sufficiently due to the high transmission ratios of the gearings. The remaining coupling effects are considered as perturbations of the control systems.

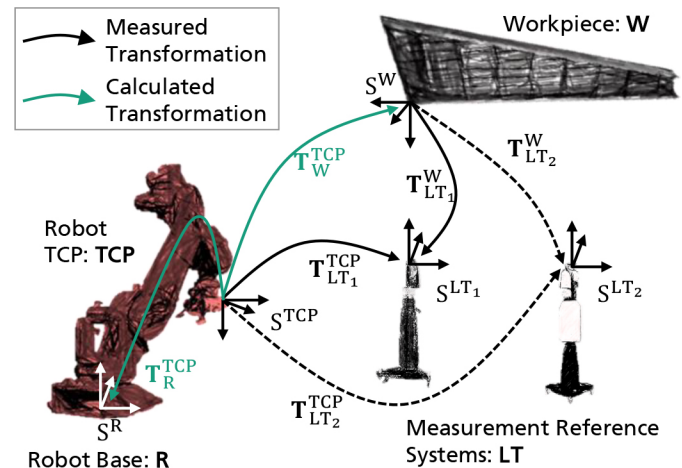


Figure 5. Transformations and relationships in test setup

There are two approaches to control the pose of a robot using an external 6DoF measurement system like a Laser Tracker which are compatible with robots that are controlled by independent cascade controllers:

1. A relative simple approach is to do all calculations in pose space. Based on the actual pose and the reference pose, a corrective pose is calculated and fed back to the manufacturer's robot controller in each control cycle. The calculation of the corrective pose can be done by simply integrating the pose error over time. This approach requires less knowledge about the behavior of the robot and can be applied in the same way to e. g. robot arms with serial kinematics or hexapods with parallel kinematics. The approach cannot take the specific dynamic behavior of the robot into account and therefore the full potential of the pose control loop cannot be tapped.

2. To put this into perspective: Assuming the commonly used trajectory speed of 3000 mm/min the robot end effector just travels about 0.4 mm in one CNC-cycle.