

High Accuracy Mobile Robotic System for Machining of Large Aircraft Components

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ABSTRACT

A mobile robotic system is presented as a new approach for machining applications of large aircraft components. Huge and heavy workshop machines are commonly used for components with large dimensions. The system presented in this paper consists of a standard serial robot kinematics and a mobile platform as well as a stereo camera system for optical measurements. Investigations of the entire system show that the mechanical design of the mobile platform has no significant influence on the machining accuracy. With mobile machines referencing becomes an important issue. This paper introduces an optical method for determining the position of the mobile platform in relation to the component and shows its accuracy limits. Furthermore, a method for increasing the absolute accuracy of the robots end-effector with help of stereo camera vision is presented. This publication shows that the mobile robotic system yields an efficient possibility for advanced machining processes of large-scaled aircraft structures in the Factory of the Future.

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INTRODUCTION

Highly growing production rates and the demand for efficient large-scale machining tools in aerospace industry have led to an increasing request for more flexible and productive manufacturing solutions [1], [2]. Industrial robots (IR) are a promising solution, although there are some major disadvantages regarding the poor absolute accuracy, low structural stiffness, gear elasticity, and limited workspace [3]. Industry and research have shown high ambitions in optimizing industrial robots. Primary aircraft structures are commonly machined by portal, gantry, or movable column machines of large dimensions [4]. Due to high investment and time-consuming referencing processes, cost-effectiveness of these machines is often non-satisfying.

With mobile robot-based solutions machining can be executed simultaneously which significantly increases productivity. The number of heavy weight mobile robotic systems in research and industry has grown substantially over the last past years. Regardless of whether for drilling and fastening operations in [5] or [6], for machining processes in [7], or for assembly tasks in [8]; the field of applications is versatile and growing continuously.

MOBILE ROBOTIC SYSTEM

The realized mobile robotic system consists of a self-driven platform including required periphery like controllers and dust-removal systems. The system has over all dimensions of 3,600 mm wide by 3,350 mm deep by 1,100 mm tall. An absolute calibrated ABB IRB6660 standard industrial robot for machining is mounted on the upper interface of the platform as it can be seen in [Figure 1](#). The robot is equipped with an IBAG HF 100A45CKP high speed spindle. An AICON MoveInspect HF stereo camera system is mounted to the platforms interface at the robot base. The stereo camera system is used to measure the spindle pose via a 3D-printed marker-device mounted at the spindle. The mass of the entire system is about 5,000 kg.

The mobile platform has two operation modes; one for driving and one for machining. In driving mode the platform is lifted by an internal mechanism to achieve a sufficient clearance to the floor. For machining mode the platform is lowered and decoupled from the driving units. This enables a solid setup at any location and avoids influences like gear backlash and elasticity of the drive units.

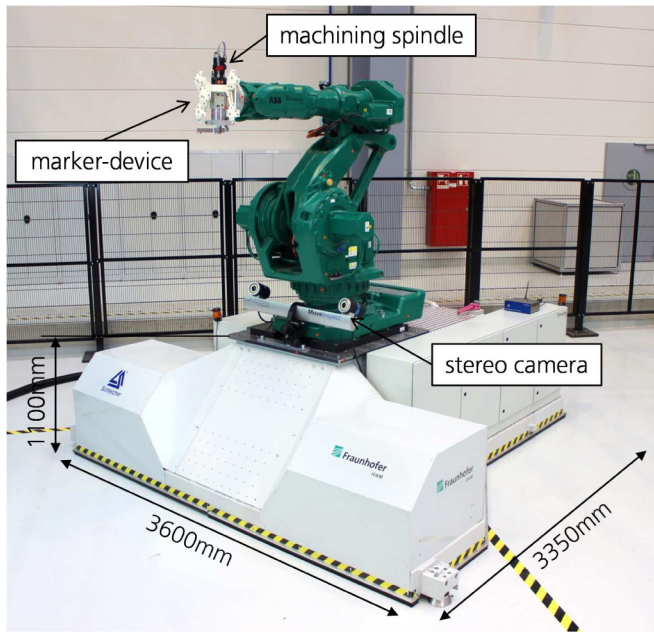


Figure 1. Mobile Robotic System for machining applications

INVESTIGATIONS ON ACCURACY OF MOBILE SYSTEM

In contrast to floor-mounted robots, a mobile solution has to ensure that the platform has no major influence on the accuracy of the machining process. Investigations based on measurements of the static and dynamic behavior show that there is a small, non-limiting impact on the entire system. In the following sections this impact will be identified.

Static Behavior of the System

A major disadvantage of industrial robots for machining operations is the comparatively low structural stiffness. Acting forces during machining operation result in deviations of the end-effectors trajectory. However, there are several approaches to reduce or compensate this issue like in [9] or [10]. With an IR mounted on a mobile platform the static behavior of the system becomes even more important regarding the additional resilient structure.

Robots usually are mounted on metal adapter plates on the floor, so torques from high payloads or arm configurations at outer workspaces can be transferred directly to the ground. The presented mobile system has no fixations to the floor, so forces have to be transmitted by the supporting feet. The platforms structure represents an additional deformable element. Even a small inclination at the interface of the platform caused by deformations may produce a non-tolerable deviation at the end-effector due to large lever arms of the robots kinematics. For this reason, an Absolute Accuracy Measurement (AAM) has been performed to compare differences between a conventional, floor mounted and a mobile configuration. In Figure 2 the experimental setup for the mobile configuration is presented.

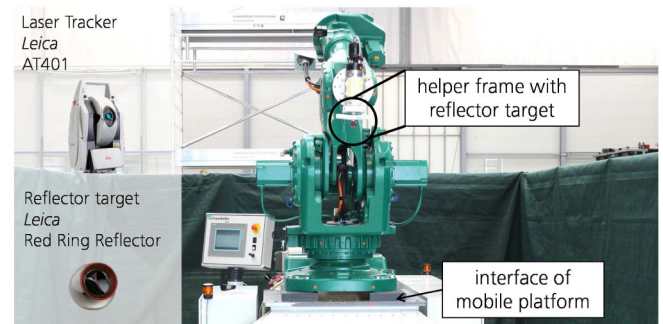


Figure 2. Experimental setup and measurement devices for the AAM

A helper frame, mounted on the machining spindle is equipped with a reflector target for a Laser Tracker. The AAM is performed by moving the robots end-effector to several measurement poses to construct frames $S^{MP_{ij}}$ in a square volume with an equal distance in all dimensions. A Laser Tracker measures each frame statically in S^{LT} . To compare the measurements of both configurations, a virtual frame S^V is constructed by 4 averaged points of 30 measurements at each position as it can be seen in Figure 3. The points arise as a result of robot movements in the xy-plane of the robots base frame S^{IR} .

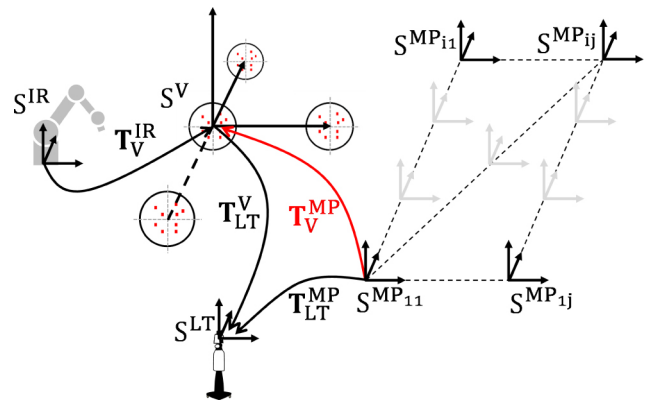


Figure 3. Relations of coordinate systems for the AAM

Here T means a homogeneous $R^{4 \times 4}$ transformation matrix. The transformation T_V^{MP} can be determined by equation (1). This procedure allows comparing multiple setups although the measurement reference has moved or the mobile system has changed its location.

$$T_V^{MP} = (T_{LT}^V)^{-1} T_{LT}^{MP} \quad (1)$$

To calculate the deviation error of the configurations, the programmed target transformations T_{ij}^T and the measured transformations T_{ij}^M are calculated by an error-transformation T_{Eij} as in equation (2).

$$T_{Eij} = (T_{ij}^T)^{-1} T_{ij}^M \quad (2)$$

With t_{Eij} the translational vector of the homogeneous matrix T_{Eij} is introduced. Figure 4 shows the deviation of t_{Eij} in the Z-axis in millimeters of the robots base frame for all measured poses i and j .

The measured workspace is displayed at the x- and y-axis in accordance with the virtual frame S^V . The black and yellow marker shows the location of the robot base.

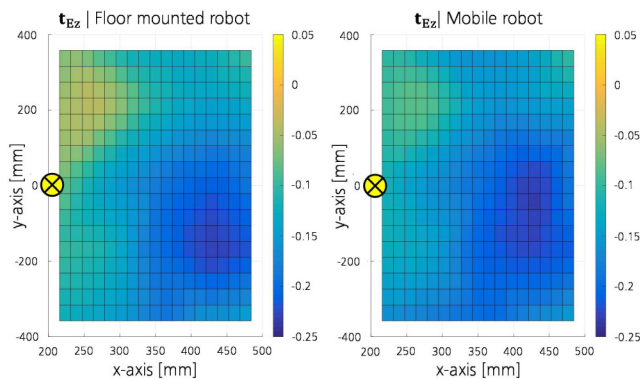


Figure 4. Results of AAM for floor mounted robot compared to mobile robot

The results show a slightly higher deviation for the mobile system with growing projection of the robot arm in the x-direction. The explanation for this result can be found in a tilt of the mobile platforms interface caused by the acting torque of the robot. However, the maximum differences between the configurations are less than 0.1 mm. Regarding the absolute accuracy of a standard industrial robot, this is a sufficient result that does not have a major impact on the systems accuracy.

Dynamic Behavior of the System

Industrial robots have shown an inferior dynamic behavior during machining operations in terms of chatter vibrations [11], [12]. From investigations like [13] or [14] typical modal parameters of serial robot kinematics are well known for floor mounted robots. Regarding mobile systems there are currently no results of the influence of the platform on the dynamics of the entire system. For this purpose, an Experimental Modal Analysis (EMA) has been performed to determine the difference between a floor mounted and a mobile robot. In both configurations an ABB IRB6660 robot is equipped with a tri-axial acceleration sensor at the machining spindle as shown in Figure 5. An impact hammer is used to apply and measure an impulse on the spindle. All signals are recorded by a data acquisition device and processed by the software ME'scope VES 6.0 to determine natural frequencies, modal damping ratios, and mode shapes by a set of Frequency Response Functions (FRF) at a low-level signal oscillation around a linearized operating point.

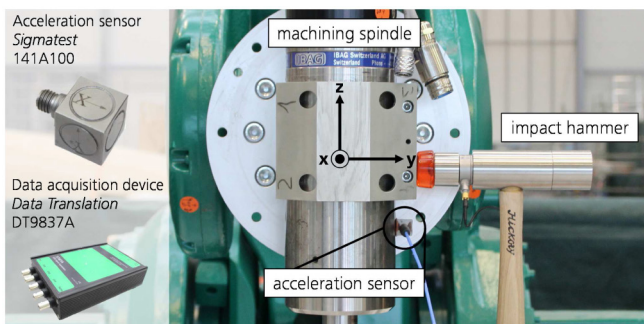


Figure 5. Experimental setup and measurement devices for the EMA

A FRF is determined by the output spectrum X and the input spectrum F as a function of the angular frequency ω that has been transformed into the frequency domain with the help of Fourier Transform [15]:

$$H(\omega) = \frac{X(\omega)}{F(\omega)} \quad (3)$$

With all sets of FRFs varying in input and output direction the transfer matrix $\mathbf{H}$ can be determined as in equation (4):

$$\mathbf{X}(\omega) = \mathbf{H}(\omega) \cdot \mathbf{F}(\omega) = \begin{pmatrix} H_{xx} & H_{xy} & H_{xz} \\ H_{yx} & H_{yy} & H_{yz} \\ H_{zx} & H_{zy} & H_{zz} \end{pmatrix}(\omega) \cdot \mathbf{F}(\omega) \quad (4)$$

This transfer function indicates the acceleration per Newton depending on the frequency. By integrating twice the acceleration, the dynamic resilience in [mm/N] can be determined. In Figure 6 the dynamic resilience of the floor mounted, fixed robot in comparison to the mobile robot is shown by way of example for the y-direction at an impact in the same direction.

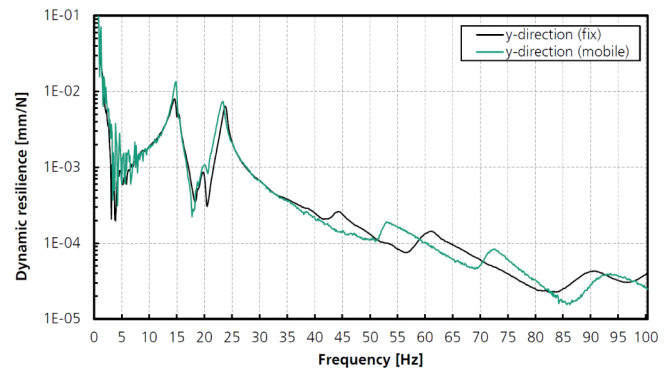


Figure 6. Dynamic resilience of floor mounted robot compared to platform mounted robot on the end-effector in y-direction based on an EMA

The results show a marginal difference between both configurations for all input and output combinations. Especially the dominating natural frequencies - in Figure 6 at 14,8 Hz and 23,1 Hz - are characterized by the dynamics of the robot kinematics. It can be concluded that there is no major impact on the dynamic behavior of the system by mounting the robot on the mobile platform. This leads to the assumption that there are no further limiting influences on the machining accuracy caused by dynamic effects.

REFERENCING

The presented mobile robotic system is designed for machining operations of large aircraft components made of Carbon Fiber Reinforced Plastic (CFRP); for example wing covers or horizontal and vertical tailplanes. Components like these often have large dimensions with up to 15 meters of length. Referencing processes of large components become even more challenging with mobile machines. Maintaining high accuracy in a large workspace requires optical measurement devices like Laser Trackers. For this reason Laser Trackers are often used in aerospace assembly. The target