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# Calibration of a parallel kinematic machine tool utilizing a MEMS inertial measurment unit

Björn Lünemann[1], Elmar Wings[1], Edward Chlebus[2]

*[1]Faculty of Technology, Dept. Mechanical Engineering, Hochschule Emden/Leer - University of Applied Sciences*
*Constantiaplatz 4, 26723 Emden, Germany*
*[2]Faculty of Mechanical Engineering, Wroclaw University of Technology*
*5 Lukasiewicza Street, 50-371 Wroclaw, Poland*

*Email: bjoern.luenemann@hs-emden-leer.de*

**Abstract**

The paper at hand illustrates a new concept for machine tool calibration utilizing a MEMS inertial measurement unit. Inertial measurement units (IMU) are devices for determining orientation and position that were initially developed for applications in the aerospace industry. Due to the triumphal procession of MEMS fabrication, the former complex and costly devices have become a popular solution for determining the orientation in recent years. Nowadays IMU`s can be found even in consumer applications like e.g. navigation and mobile devices. Unfortunately, the accuracy and reliability of the devices was not sufficient for machine tool calibration. However, this situation has changed with the newest incarnation of MEMS IMUs which have been introduced within the last few years and are commercially available now.
At the University of Applied Science Emden/Leer a new calibration system is under development that incorporates a state of the art industrial grade MEMS IMU. Within the course of the paper we illustrate our concept for integration of the MEMS-IMU into the control system environment of the machine tool.

Keywords: machine tools, calibration, inertial measurment unit, MEMS

## 1. Introduction

Independent from the kinematic design of a machine tool, the industrial application requires an efficient calibration method for the investigation of its accuracy. The accuracy of a machine tool is primarily defined through geometrical and dynamical machine tool properties. Any deviation of the tool center point from the programmed position will be represented as geometric deviation in the workpiece. Therefore, it is necessary to measure deviations of the machine movements and eventually compensate them.

### *1.1. Calibration process*

The first step in the calibration process is the establishment of a kinematic model of the machine tool. The goal within this step is to find an equation describing the pose of the machine tool dependent on the parameters that describe the geometry and the actual orientation of the joints. The following equation from [1] depicts this dependency:

$$P = f(\eta, \theta) \tag{1}$$

P: Pose in task space
$\eta$: Vector of constants describing the geometry of the manipulator
$\theta$: Vector of joint displacements for any particular pose

A machine tool will most definitely be affected by errors, induced during the manufacturing and assembly. These might be deviations in the length of links or joint orientations. Hence, the kinematic model developed in the first step must be extended.

The task is to find the error parameters that have a significant impact on the position and orientation of the TCP. In other words: Assess the impact of changes in uncertain parameter values on the output of the model. For the extended kinematic model only the parameters with major impact will be used.

Calibration requires an accurate and reliable method for measuring the end effector pose or a subset of the pose in different joint orientations. Furthermore, a strategy for carrying out the measurements must be defined. The observation strategy should be designed in such a way, that the required number of measurements can be reduced to minimum.

The identification step is the main challenge within the calibration process. The purpose of this step is to choose the vector of model coefficients $\eta$ that will minimize $\delta P_{pi}$ in some sense for the set of measured poses. [1]

$$\delta P_i = P_{mi} - P_{pi} \tag{2}$$

$P_{mi}$: Measured pose at i-th joint displacement
$P_{pi}$: Pose predicted by kinematic model
$\delta P_{pi}$: Difference between pose prediceted by the kinematic model and the measured pose for the given joint displacement

Taking into account Equation 1 we can write:

$$\delta P_i = P_{mi} - f(\eta, \theta) \tag{3}$$

The final steps are the compilation of a calibration protocol and the adaptation of the kinematic model, taking into account the parameters found in the identification step of the calibration process.

## 2. Calibration of a parallel kinematic machine tool utilizing an inertial measurement unit (IMU)

The choice of the measurement technology and strategy is a crucial part within the calibration process.

In recent years, some research has been conducted, that investigated the utilization of MEMS inertial sensors for calibration. Tabatabai [2] used MEMS inertial sensors for calibration of a planar kinematic. Guanglong [3] investigated the utilization of a MEMS IMU for calibration of a serial robot. Gao, et. al. [4] investigated the utilization of an inertial measurement unit for a parallel kinematic machine tool.

### *2.1. Inertial measurement unit*

An inertial measurement unit (IMU) is a device that can be used to determine the orientation and position of an object in space. For this purpose t contains two triplets of sensors. One of these consists of three angular rate sensors, while the other consists of three acceleration sensors. In both triplets the sensors are oriented orthogonal to each other. If the initial position and velocity of an object are known, the position can be calculated by a simple double integration of the acceleration over time. This basic principle is also used for IMU-navigation. However, the method for integrating the data is complex. [5], [6], [7] The calibration of the IMU itself is a prerequisite for successful measurements. Sensor errors like bias, scale factor non-linearity, misalignments between sensor axes and noise must be identified and compensated. Several calibration routines have been developed featuring different experimental setups and mathematical methods for determination of these error parameters. [5], [8] Additionally, it is crucial to accurately determine the orientation of the axes of the IMU with respect to the inertial reference frame of the earth and the measurement frame (e.g. machine tool coordinate system). [9]

## 3. Development of an IMU-based calibration system

The study of former research showed that accuracies in the µm-Range have been achieved by utilizing inertial sensors as a means for measuring. However, until today, an IMU-based calibration system for machine tools is not available. The main reason for this is the fact that so far no MEMS IMU existed which offered sufficient measurement accuracy, stability, small dimensions and a reasonably low price. In 2011 Epson Technology announced an industrial grade IMU that is manufactured using a novel micro fabrication technology called QMEMS. Compared to common MEMS IMUs made from semiconductor-material, the novel technology allows a higher signal to noise ratio, higher stability, higher sensitivity and low zeropoint drift.

An engineering sample of the QMEMS IMU G-350 is currently used within a cooperative research project between the Technical University Wroclaw and the University of Applied Science Emden-Leer. The goal is to develop a calibration system for parallel kinematic machine tools and to investigate the performance of a QMEMS IMU.

Figure 1 illustrates the calibration system that makes use of the open architecture of the TwinCat 3 environment. The inertial measurement unit transfers measurement data to the control system in real time.

The core of the IMU data evaluation is an extended kalman filter. This well-known filter algorithm has been adapted to the specific needs of the application at hand. The main task of the kalman filter is to calculate the best estimate of the position and orientation. Both, data from the IMU as well as nominal values delivered by the CNC are fed into the algorithm, taking into account the noise in the IMU data and in the encoder values of the machine tool itself. Finally, the algorithm provides data for compensation of deviations of the TCP.

For the development and testing of the IMU-based calibration system a delta robot has been designed and set up. The robot can be classified as a three translational degree of freedom parallel manipulator.

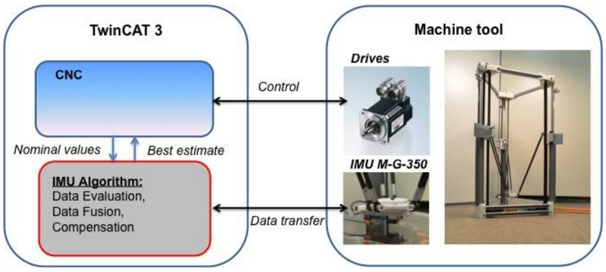

**Figure 1:** Concept for IMU-based calibration system.

## 4. Conclusion

A novel calibration system for machine tools utilizing a QMEMS IMU is currently under development. The hard- and software infrastructures for real time measurement and IMU data transfer have been implemented. A delta robot has been set up for testing purposes. First experiments prove that the basic functionality has been achieved. However, further development is necessary in order to improve the algorithms for evaluation of the IMU data.

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