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# Active Compensation of Dynamic Errors in a Coordinate-Measuring Machine *

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**Abstract:** Measuring systems for production quality control face increasing demands in both measurement velocity and accuracy. The undesired dynamic effects of measuring machines pose more stringent limits to the measurement velocity than modern optical sensors for surface metrology, for example chromatic confocal point sensors. These dynamics are investigated at an exemplary coordinate measuring machine and their negative effects on the measured values are described. A compensation system for the reduction of the induced errors based on internal deviation sensors is proposed and investigated. Subsequently, a dynamic model for the machine's dominant dynamic effects is identified in order to transfer the compensation system to machines without internal deviation sensors.



*Keywords:* Precision measurements; Mechanisms; Micro and Nano Mechatronic Systems; Motion Control; Product quality; Control precision; Control applications

## 1. INTRODUCTION

Reduced production cycle times, increasing demands on accuracy and increasing manufacturing variety raises the demand for fast automated inspection of all manufactured parts. In both series production and small-batch production of high-precision mechanical components, thorough quality inspection procedures require highly flexible and fast inspection machines and strategies which are able to adapt to the broad range of geometric shapes and surface quality requirements of the components.

Modern surface metrology sensors, for example used by Gronle et al. (2013), do allow for fast measurements and large surface inspection velocities. The accuracy of these fast measurements is limited by the positioning accuracy of the measuring machine. Manufacturing accuracy and limited stiffness of bearings and guideways constitute limitations for the machine's positioning accuracy. While static errors caused by limited manufacturing accuracy and the compensation of these are subject of many publications in the fields of precision engineering and metrology, e.g. Weekers and Schellekens (1995, 1997), the excitation of dynamic errors is typically avoided by conservative limits on the motion velocity and acceleration of the measuring machine. These limits ensure that the undesired mechanical dynamics of the machine are not excited, but also result in large measurement times and obstruct the use of the sensor's full capabilities.

In order to overcome the limitations on the measurement velocity, we propose to augment the position control system by an online error compensation system. The closed-loop machine axes control system drives the axes such that the impact of undesired dynamic errors on the sensor position is compensated for. This augmented control system reduces the resulting sensor position error caused by undesired dynamic effects. It can thus be transferred from measuring machines to machine tools.

Analyses of measuring machines' dynamic errors based on internal or external sensors have been presented by Weekers and Schellekens (1995, 1997) and Cheng et al. (2009), finite elements analysis were presented Mu and Ngoi (1999) and Liu et al. (2009). An analysis based on a neural network approach was conducted by Dong et al. (2002, 2003). An analysis regarding the machine's behavior for certain specimen geometries is presented by Pereira and Hocken (2007). However, all these publications aim at a correction calculation after the measurement process, not an online error reduction system which can also be applied to machine tools. Dynamic analyses with the objective of improving the mechanical design have been presented by Dong et al. (2003) and de Nijs et al. (1988). Chang and Spence (2007) present a control system for the reduction of the gantry yaw error of a gantry type measuring machine. A general online error compensation system which is based on closed loop position control has not been suggested.

## 2. DEMONSTRATOR SYSTEM

Our demonstrator system is based on a modified *Mahr MarForm MFU 100* coordinate measuring machine, Fig. 1. This multi-sensor measuring machine is equipped with four

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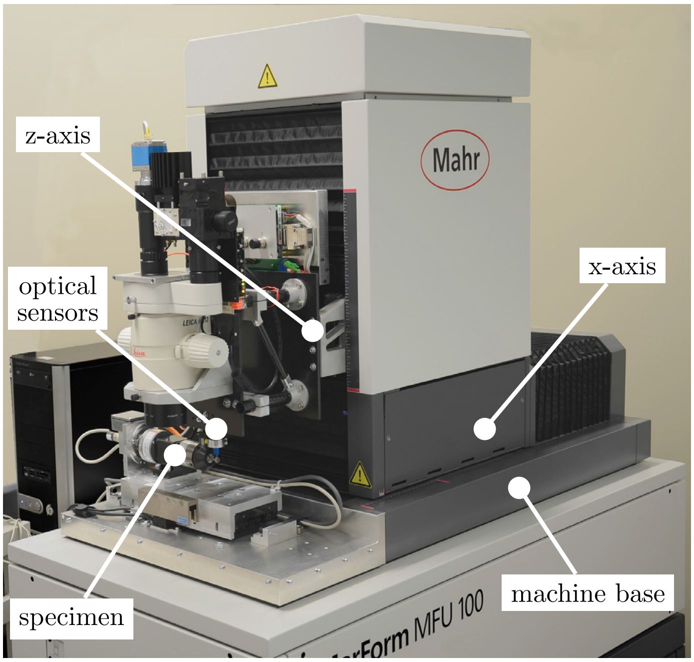


Fig. 1. Multi-sensor measuring machine, *Mahr MarForm MFU 100* with component positioning system, fringe projection microscope and chromatic confocal point sensor.

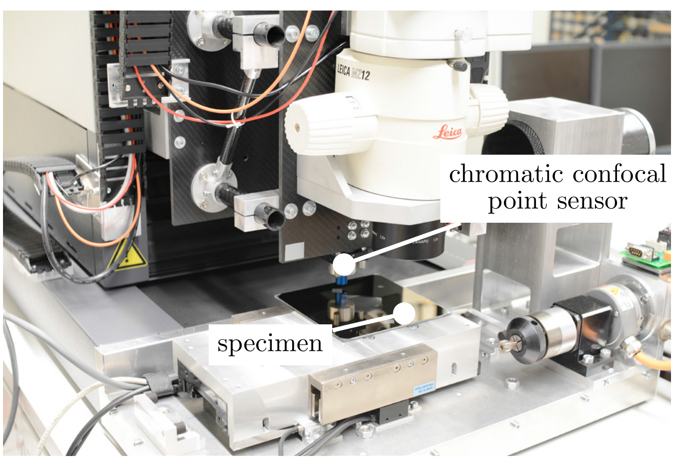


Fig. 2. y-axis and b-axis with chuck to clamp gearwheels as specimen. A chrome mask as specimen is mounted on the y-axis and the chromatic confocal point sensor is in position to scan the mask's surface. The chrome mask is used to investigate the dynamic effects described in this contribution.

motion axes, the original x- and z-axis and the additional y- and b-axis specifically designed and manufactured to position specimen such as semiconductor wafers or gearwheels, Fig. 2. The x- and z-axis are driven by rotational DC-motors and frictional engaged backlash-free spindle-nut systems. The rotational b-axis is driven by an ironless DC-motor, the y-axis is equipped with two ironless linear motors with electronic commutation. The x- and z-axis are equipped with recirculating ball bearing guides for the linear motion. The motion of the axes are recorded by high-resolution incremental encoders, with a resolution of 1 nm in x and z, 10 nm in y and 0.13″ in b. The workspace of the multi-sensor measuring machine covers 200 mm × 100 mm × 250 mm × 360 °.

All measurement signals are acquired at a sample rate of 2 kHz and fed to the control system. The control system is based on a *dSpace DS-1005* 1 GHz PowerPC and acts as a position control system by reading the incremental encoders and deviation sensors and setting the motor currents of the axes' drives. The control algorithms as well as path and trajectory generators are also implemented in this system. Two offline trajectory generators were developed at our institute and are in use in our research projects. Both of them are used with the *MFU 100* in this project, the approach based on interpolation of straight lines developed by Ruppel et al. (2008) is appropriate for measurement tasks with relatively small numbers of target points (up to twenty), while the approach based on approximation and spatial filtering presented by Keck et al. (2015) is better suited for measurement tasks with many (several hundred) target points, for example generated from CAD data or noisy master measurements. In addition, an online path and trajectory generator is implemented to generate appropriate reference values based on joystick-commands in manual mode. Further information on this additional system were published by Knierim and Sawodny (2012).

The original tactile sensor of the *MFU 100* was replaced by two optical sensors. A fringe projection microscope is used to obtain overall views of the inspected component as well as some detail measurements, Fig. 1. The second sensor used for high-resolution scanning of the inspected surfaces is a *Precitec CHRocodile S* chromatic confocal point sensor with a resolution of 10 nm and a range of 300 µm. The measurement value of the point sensor is fed to the *dSpace* control system at 2 kHz. An overview of the automation and control system can be found in Keck and Sawodny (2014).

## 3. UNDESIRED DYNAMIC EFFECTS OF THE DEMONSTRATOR SYSTEM

The *MFU 100* displays undesired dynamic effects in the x- and the z-axis at large velocity. In this contribution, we regard the dynamics excited by fast measurement motions of the x-axis as typical examples for undesired dynamic effects. The relevant degrees of freedom for this example are the positions of the x- and z-axis $x$ and $z$, as well as the rotation of the x-axis relative to the machine base $x_\mathrm{r}$ which is caused by the limited stiffness of the x-axis guideway. Bending within the machine column gives rise to the rotation of the z-axis guideway relative to the x-axis $xz_\mathrm{r}$ and limited stiffness of the z-axis causes the rotation $z_\mathrm{r}$ of the sensor mounting relative to the z-axis guideway. These effects as well as the encoders, angular deviation sensors and the chromatic confocal sensor are depicted in Fig. 3.

The rotations cause a deviation of the real position $(x_\mathrm{TCP}, z_\mathrm{TCP})$ from the position measured by the encoders $(x_\mathrm{enc}, z_\mathrm{enc})$. The real position $(x_\mathrm{TCP}, z_\mathrm{TCP})$ can be calculated from the encoder positions $x_\mathrm{enc}$, $z_\mathrm{enc}$ and rotations $x_\mathrm{r}$, $xz_\mathrm{r}$ and $z_\mathrm{r}$. As can be seen in the schematic Fig. 3, the undesired dynamic effects result in both a deviation of the measurement value and the measurement position on the specimen surface.

The deviation caused by dynamic effects is shown in the measurement in Fig. 4. A fast motion of the x-axis with