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Design and experimental validation of an ultra-precision Abbe-compliant linear encoder-based position measurement system

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ABSTRACT

The design and development of an Abbe-compliant linear encoder-based measurement system for position measurement with a targeted 20 nm uncertainty ($k=2$) in machine tools and CMMs is presented. It consists of a linear scale and a capacitive sensor, mounted in line on an interface which is guided in the scale's measurement direction and driven by a linear motor based on the output signal of the capacitive sensor. The capacitive sensor measures the displacement of a target surface on the workpiece table. The functional point, which is the center of a tool or touch probe, is always aligned with the scale and capacitive sensor such that this configuration is compliant with the Abbe principle. Thermal stability is achieved by the application of a thermal center between the scale and capacitive sensor at the tip of the latter, which prevents both components to drift apart. Based on this concept, a prototype of a one-DOF measurement system was developed for a measurement range of 120 mm, together with an experimental setup aimed at verifying the reproducibility of the system for changing ambient conditions of $\pm 0.5\,^{\circ}$C and ± 5%rh and the repeatability during tracking of a target surface over a short period of time. These experiments have shown that the measurement uncertainty of the one-DOF system is below 29 nm with a 95% confidence level.

1. Introduction

For centuries, the improvement of machine tool accuracy has been the key enabler for the development of new technologies. The accuracy of machine tools depends mostly on the positioning accuracy of the tool with respect to the workpiece. The largest influences on this positioning accuracy are thermo-mechanical errors and geometrical errors [1]. Thermo-mechanical errors arise due to expansion and deformation of the machine tool structure by temperature changes, while geometrical errors are mainly because of inaccuracies in the movement of the slides. Reduction of thermal errors is currently achieved by placing the machine in a temperature-controlled environment, by employing low-expansion—yet expensive—materials for the machine structure and by modeling and compensating thermal errors [2]. Geometrical errors are generally reduced by applying air bearings or hydrostatic bearings [3], by Abbe offset reduction [4] or by error measurement and compensation [5].

However, the application of certain precision engineering design principles, such as functional separation of the force loop and the metrology loop and the Abbe principle, could be more thoroughly exploited to increase the accuracy of machine tools even further [6–8]. These principles have been applied in several specialized ultra-precision machine tools and CMMs based on laser interferometer position measurement [9–14] and in a few CMMs utilizing linear encoders [15,16]. Kunzmann et al. [17] compared the uncertainty of laser interferometry in air to linear encoder position measurements. They concluded that the uncertainty of laser interferometers over a short time period increases with measurement stroke (L_s) by $0.2 \times 10^{-6} \cdot L_s$ (coverage factor $k=2$ [18]), while for linear encoders the stability was practically independent on the measurement stroke. For this reason, encoder grids are used in the latest generation of 193 nm wavelength lithography machines [19]. The application of laser interferometry in machine tools requires additional measures to maintain the stability of the refractive index [20], which renders these machines complex and less cost-effective. The application of linear encoders compliant with the Abbe principle in three DOFs in machine tools could enhance the accuracy considerably, but has not yet been investigated. A full three-DOF application of the Abbe principle with linear encoders has only been realized in a CMM [16], where it was limited by a small work volume.

Therefore, the aim of this research is the development of a linear encoder-based position measurement system for machine

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tools that enables Abbe-compliant measurement in three DOFs. To enable sub-100-nm accurate machining for *normal* machine tools [21], at least five times lower measurement uncertainty is required, namely 20 nm (k = 2). This goal should be reached for displacements in the order of 100 mm in standard metrology room ambient conditions of 20 ± 0.5 °C and ±5%rh.

This paper presents the latest results in the development of this measurement system. The proposed concept has been selected from a number of embodiments which have been introduced in [22]. The chosen embodiment of the measurement system was discussed in [23], although no details on the design were given. Bosmans et al. [24] presented the performance of the system in tracking of a target surface and in [25] the origin of the dynamic errors of the measurement system was investigated. Bosmans et al. [26] elaborated on the calibration of the measurement system.

The current work presents the final updated uncertainty budget and detailed design of the measurement system and elaborates on the experiments that were conducted to verify the budgeted uncertainty. First, Section 2 explains the measurement system concept. Consequently, Section 3 describes the mechanical design of the one-DOF prototype, called *Moving Scale* (MS) system. The sources of measurement uncertainty are identified and presented in an uncertainty budget in Section 4, where each uncertainty component is discussed in more detail. Section 5 discusses the design of an experimental setup for determination of the reproducibility under changing ambient conditions and the repeatability of the one-DOF MS system and encompasses the results of these experiments. Finally, an upper bound on the measurement uncertainty of the MS system is estimated.

2. Conceptual layout

The generalized Abbe principle [27], which was reformulated by Bryan [28], states that *the path of the effective point (EP) of a displacement measuring system should be collinear with the path of the functional point (FP) whose displacement is to be measured. If this is not possible, either the slideways that transfer the displacement must be free of angular motion or angular motion data must be used to calculate the consequences of the offset*. It has been derived in [13] that the FP of a system with a spherical end-effector, such as a touch probe or a spherical tool, equals the center of that end-effector. To achieve Abbe-compliance for a two- or three-DOF system with a minimum amount of linear encoders and moving elements, the FP should remain stationary with respect to the reading heads and coincident with the path of the EPs of the linear encoders. The EP of the linear encoder is the readout position on the scale. This kind of configuration can only be attained if the encoders measure the movement of target surfaces surrounding the workpiece while at the same time allowing these target surfaces to move relatively with respect to the encoders in a direction perpendicular to the encoders' measurement direction.

The proposed configuration is illustrated in Fig. 1 in two DOF. The scales are mounted on an interface that is guided in the measurement direction and the reading heads of the encoders are connected to a stationary metrology frame. To allow relative movement between the encoder and its respective target surface in a direction perpendicular to the encoder's measurement direction, a non-contact displacement sensor is added in line with the scale in between the target surface and the scale. The scale interface is actively driven by a linear actuator based on the output of the displacement sensor. In this way, the scale interface follows the movement of the target surface in the measurement direction. The position measurement of the target surface x_{target} is constituted by

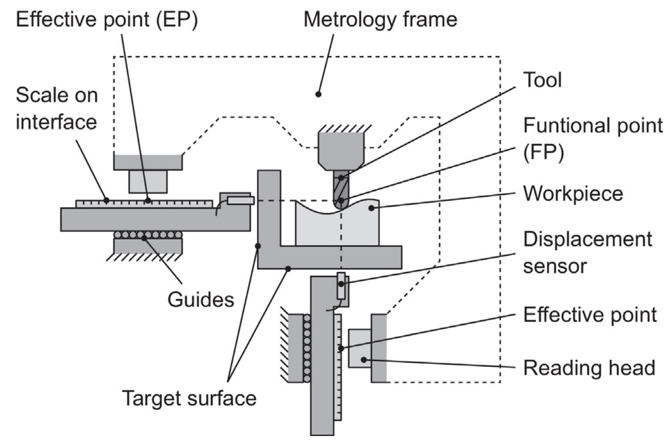

Fig. 1. Configuration of linear encoders such that the path of the functional point and the effective point of the scale are in line.

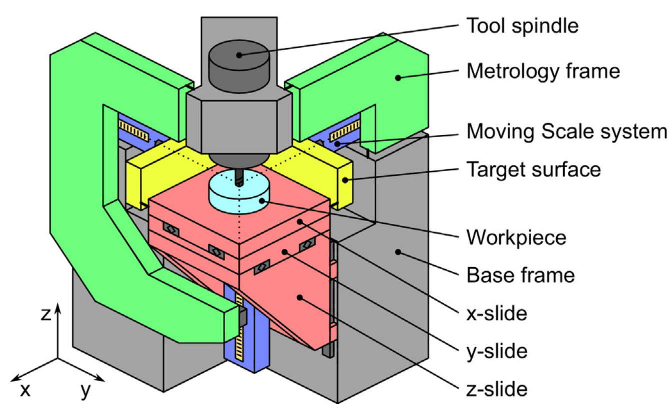

Fig. 2. Concept of Moving Scale system on a three-DOF machine tool.

the measurement of the linear encoder x_{MS} and the displacement sensor x_{DS}:

$$x_{target} = x_{MS} + x_{DS}. \tag{1}$$

Therefore, the linear actuator should only keep the displacement sensor within its measurement range such that tracking errors do not result in measurement errors.

Fig. 2 shows how this concept can be applied on a machine tool in three DOF. Target surfaces are added to the workpiece table and the base frame is extended to integrate the MS systems. Metrology frames that hold the MS systems' reading heads are connected to the base frame and ensure a stable, functionally separated closure of the metrology loop [6,7]. For low-end applications, the metrology frames could be omitted and the reading heads could be directly attached to the machine base frame.

3. Design of a one-DOF MS system prototype

The geometrical arrangement of the major elements in a one-DOF prototype of the MS system with a measurement range L_m of 120 mm is shown in Fig. 3. The utilized measurement stroke L_s of the system equals 107 mm. This value originates from the intended use of the MS system for the z-axis of an ultra-precision five-axis grinding machine with a stroke of 107 mm [29]. Fig. 4 displays a picture of the prototype, excluding the metrology frame and the reading head. The linear encoder is a Heidenhain LIP 281 and a Lion Precision C5-D capacitive sensor is integrated as the displacement sensor.