# Experimental validation of the reproducibility of a position measurement system with nanometre uncertainty

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## Abstract

Machine tools require ever increasing accuracies. A metrology system using linear encoders according to the Abbe-principle and functional separation of the structural and metrology loop, called 'moving-scales', has been developed to address this requirement. This work shows the experimental results of the thermal stability of a 1-DOF moving-scale system on a dedicated measurement setup.

## 1. Introduction

Machine tool accuracy needs to be continuously improved to meet the challenges in manufacturing today and in the future. The largest sources of errors in modern machine tools are thermo-mechanical errors and geometrical errors. These errors can be significantly reduced by proper application of precision engineering design principles such as functional separatation of the metrology loop from the structural frame and measurement compliant with the Abbe and/or Bryan principle. KU Leuven has proposed a metrology concept for machine tools using functionally separated metrology frames [1] and a metrology configuration called 'moving-scales' allowing Abbe-measurement with linear encoders [2]. The layout of a machine tool incorporating these concepts is schematically shown in figure 1. A prototype of the moving-scale measurement system has been developed and an error budget predicted a measurement uncertainty of 20 nm for 1 °C temperature changes [3].

## 2. Setup for determining the reproducibility

Figure 2 depicts the dedicated setup for determining the reproducibility of a 1-DOF moving-scale measurement. The position measurement of the moving-scale is compared to the position measurement of a reference scale that is aligned with it.

Temperature expansion of the metrology frame is compensated by using a second reading head on the reference scale. Table 1 gives an overview of the uncertainty budget of the setup. The largest uncertainty contribution arises from the uncertainty of the metrology frame's thermal expansion compensation.

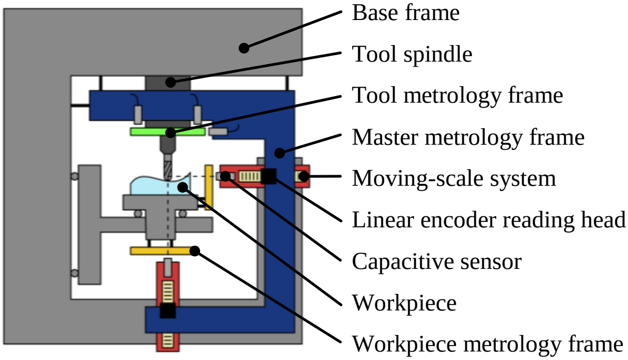


Figure 1: Layout of the integration of metrology frames and a moving-scale measurement system in a machine tool.

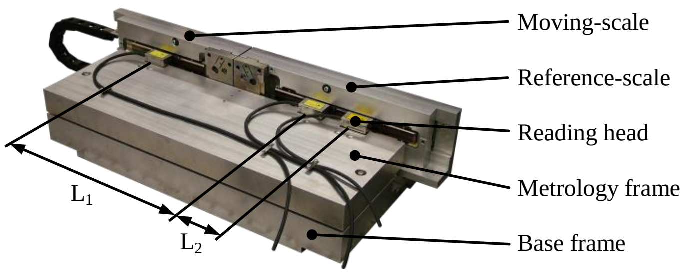


Figure 2: Test setup for determining the reproducibility of the moving-scale measurement system.

# 3. Experiments

## 3.1 Temperature stability

The setup has been placed in a temperature controlled environment at (20.0±0.5) °C. An aluminium shield with a thickness of 5 mm around the metrology frame ensured a uniform temperature distribution. A PVC enclosure measuring 650 mm × 650 mm × 500 mm has been put over the setup to filter fast temperature fluctuations. Temperature was measured inside the enclosure on top of the aluminium shield.

Figure 3 gives a graph of the temperature and the position measurement error. Temperature changes of 0.7 °C inversely correlate to a measurement error of approximately 40 nm. More rapid fluctuations, which are not in correlation with temperature, could not yet be explained. The error however remains below the expected measurement uncertainty of 37 nm for a 0.5 °C temperature change.

Table 1: Uncertainty budget of the reprodicibility setup

| **Component** | | $U_{k=2}$/nm |
|---|---|---|
| **Affecting reproducibility** | Thermal erorrs for ΔT=0.5 °C | 37 |
| | Dynamic errors and sensor noise | 9 |
| | Non-repeatable geometric errors | 5 |
| **Not affecting reproducibility** | Calibration errors | 13 |
| | Repeatable geometric errors | 5 |
| **Combined measurement uncertainty** | | 41 |

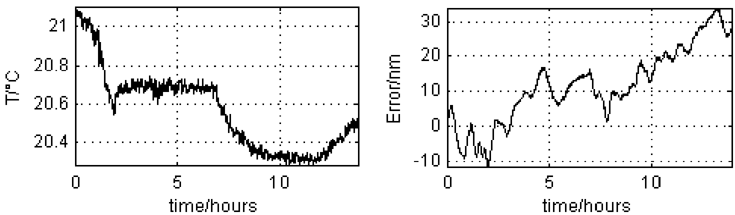


Figure 3: Temperature in the metrology room and resulting position measurement error of the reproducibility determining setup.

### 3.2 Tracking of reference scale within capacitive sensor range

The transfer function from the linear motor to the capacitive sensor has been identified, which shows an eigenfrequency ranging from 189 Hz to 242 Hz. This eigenfrequency originates from the guide flexibilities and depends on the moving-scale position. A dual-loop feedback controller has been designed, in which the feedback signal of the linear encoder is used in the inner velocity loop and the capacitive sensor signal in the outer position loop. By setting the reference signal of the capacitive sensor to zero volts, the control loop makes the moving-scale to track the movement of the reference-scale. The gap change due to the tracking errors stays within the ±25 µm measurement range of the sensor, which can be seen in figure 4.

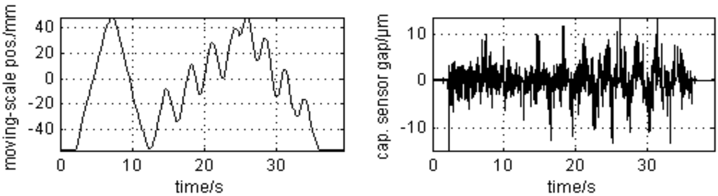


Figure 4: Variation of the measured gap by the capacitive sensor during tracking of the motion of the reference-scale by the moving-scale.

## 4. Conclusion and future work

The thermal stability of a 1-DOF moving-scale system has been assessed and it has been demonstrated that the measurement errors due to temperature changes of 0.7°C were approximately 40 nm. Further experiments will focus on the determination of the repeatability of the system due to dynamic errors, sensor noise and non-repeatable geometric errors.

## 5. Acknowledgements

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