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Self-calibration using advanced algorithms on a multi-probe system

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Abstract
This article describes the outcome of a method to perform online self-calibration of a position measurement system. It is applied to a linear encoder, but has potential for use in rotating or multi-DoF systems. It is based on a three-probe measurement in which the intermediate probe distances determine a calibration grid. This leads to an error profile that is virtually free of integration errors. A smart algorithm allows to extract the relevant data efficiently from online position data. Experimental results demonstrate the feasibility of the proposed method.

Keywords: Metrology, Self-calibration, Algorithm

1. Introduction

Accurate positioning systems require an advanced position measurement device. Ideally, its position data is linearly dependent on the actual position. In reality nonlinear behaviour is present, such as an encoder scale with local scale deformation due to mounting stresses. Such systems are often calibrated offline, using a separate measurement tool, to correct for any repeatable metrology errors. However, this tool may become impractical e.g. if the system is difficult to access (vacuum operation), if the machine's up-time is critical or in the case that it is too expensive. If the positioning measurement system could self-calibrate on-the-fly, such a calibration tool would become obsolete.

Literature describes a number of multi-probe self-calibration methods [1-4]. For its favourable properties with respect to reconstruction error, noise sensitivity and mounting tolerance sensitivity, the so-called inclination method has been implemented in an experimental setup. This method uses information of multiple encoders. It is applied to a system that requires a high linearity over a long range. The nonlinearity of its ruler-based metrology system, caused by e.g. manufacturing errors in the ruler, local thermal expansion or mounting stress of the ruler, is estimated using an advanced algorithm. This method is described in Section 2.

Experiments have been conducted, which validate the feasibility of this self-calibration. They demonstrate the opportunities that are offered using multiple encoder heads. It allows for an in-line calibration that does not require a separate calibration tool and can be conducted on-the-fly. The experiment and results are discussed in Section 3, followed by the conclusions in Section 4.

2. Inclination method

The method that is discussed in this paper is based on measured integrated differential profiles (groups) as error shapes. Each group is sampled with a step length L, which is equal to the distance between two probes on the mover.

Figure 1 basically shows this measurement principle. The curvy, slightly tilted line represents the nonlinearity of the scale. The rectangular blocks represent the linearly traveling mover. It has two sensors, X_A and X_B, separated by a distance L. The length of the arrows below these sensors represents the error of the signal as measured by a sensor on that particular position. If the mover is stepped with a step size L, a differential error shape profile (as opposed to an integrated profile) of the scale nonlinearity is obtained with a grid pitch equal to L. Referring to Figure 1, with each calibration step the mover goes rightwards and encoder X_A is moved to the previous position of X_B. In this way the integration error is eliminated. However, this is at the cost of a poor spatial calibration resolution.

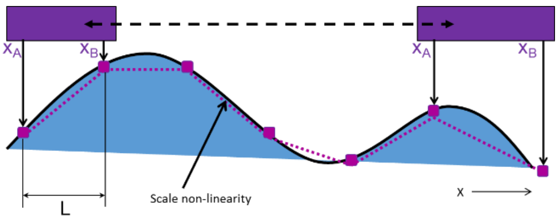

Figure 1. Inclination method for a group with grid pitch L. The squares represent the equally spaced measurement points.

The required calibration grid pitch S is generally smaller than L. In such case multiple L-spaced groups are measured which have an offset S with respect to each other. This is illustrated in Figure 2, where the original group (squares) with spacing L is complemented with two more groups (circles, rhombi) that have the same spacing L, but have a relative sampling offset S. By determining the error offset between all groups, an accurate error profile can be obtained.

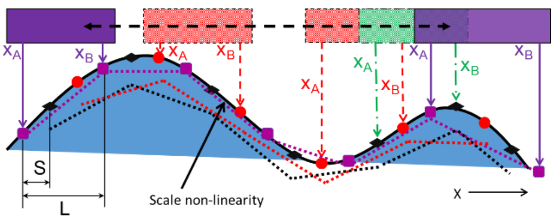

Figure 2. If the required grid pitch is smaller than the sensor spacing, multiple groups can be combined.

Another method to achieve such a resolution improvement is to add a third sensor to the mover, such that the greatest common divisor of their intermediate distances equals S. The third probe is then used to link the various measurement groups together without errors. This method is used in this paper.

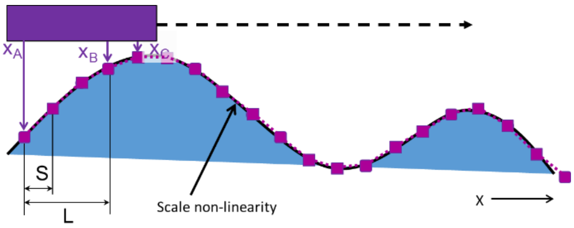

Figure 3. Using more than two sensor heads allows for a directly coupled measurement on all calibration grid points.

A smart algorithm distils and pre-processes the relevant data from a continuous movement of the mover over the scale. It eliminates the need to step through all calibration grid points. An error profile is then calculated (online but not real-time) and can be used immediately for self-calibration of the system.

3. Experimental setup and results

Figure 4 shows the experimental setup. A linear mover on air bearings moves over a scale, which is laid out straight on a vibration-isolated granite table. A polycarbonate cover dampens temperature changes. The mover configuration discussed in this paper has three encoders, similar to Figure 3.

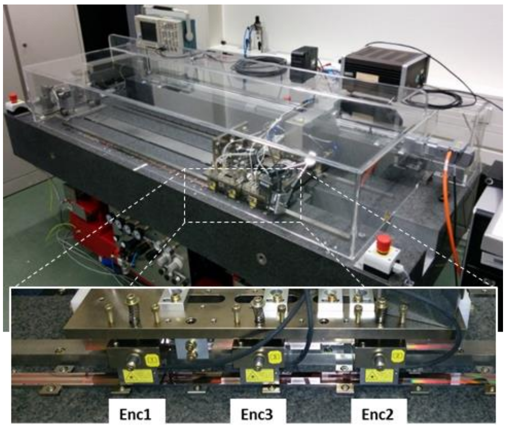

Figure 4. Experimental setup with three encoders.

Figure 5 shows the difference between the three incremental encoder position signals. Given the assumption that the physical distance between the encoder heads does not change during calibration, these readings are our input to estimate the nonlinearity of the encoder scale.

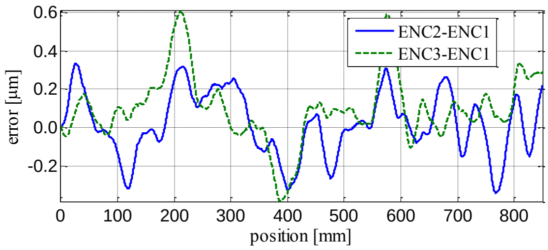

Figure 5. Position difference obtained by the three sensors on all mover positions.

These data are processed by the aforementioned algorithm to obtain an error shape profile of the ruler. Figure 6 shows two processed error profiles that were obtained on the same setup from measurements that were done 6 months apart. The probe geometry is different in both measurements, to verify if the error profiles are similar. The various mounting threads to accomplish this different geometry can be seen in the insert of Figure 4. The similarity between the two curves shows the robustness of the method.

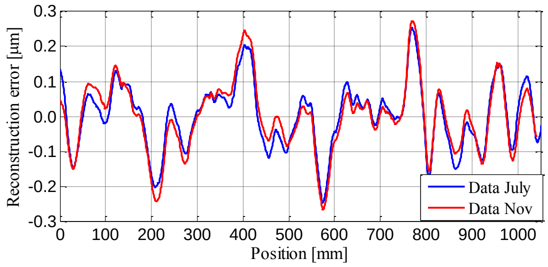

Figure 6. Reconstructed grid error on a 1mm calibration grid pitch. The two curves show the reconstructed errors based on different sensor configurations (i.e. different offsets) obtained with a 6-month interval.

From the sensor layout, grid pitch and number of measurement points, it is possible to calculate the calibration uncertainty relative to the sensor uncertainty. This uncertainty is highest near the edges of the ruler. If two grid calibration points can be coupled to each other in many ways (see Figure 3), this decreases the uncertainty. The amount of steps necessary to make this coupling adversely effects this same parameter. These parameters are the main contributors to the wavy behaviour and the U-shape of the grid uncertainty shown in Figure 7. As such, more encoders result in better performance, as long as their intermediate distance is chosen smartly.

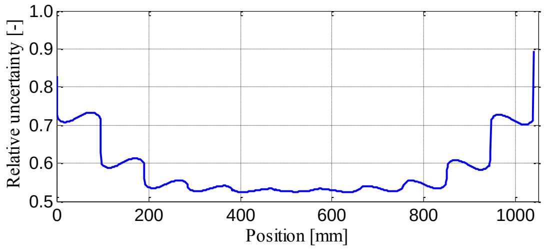

Figure 7. Ratio of grid uncertainty over sensor uncertainty.

4. Conclusion

This article presents a method for self-calibration of positioning systems. By smart placement of multiple sensing probes on the mover the calibration pitch can be freely determined. With more than two probes, a measured integrated differential error shape can be obtained that is virtually free of integration errors. A smart algorithm distils the relevant grid data from a continuous movement trace and processes it to obtain an error profile of nonlinearities in the ruler. This is done online but not real time and can be used directly for self-calibration. The method is applied to a linear drive in this paper, but is also suitable for rotating devices or for multi-DoF devices.

An experiment successfully shows the feasibility of the concept for a linear encoder with three probes. Two measurements done with an interval of 6 months and a different encoder geometry show nearly the same results, thus showing the robustness of the chosen method.

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