

# Design of a 3D-Coordinate Measuring Machine for measuring small products in array

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## Abstract

This paper describes the machine lay-out of a scale based stand-alone design, presently under construction, aimed at an accuracy of 25 nm in a 50×50×4 mm<sup>3</sup> volume. The scales have 1 nm resolution and are direct driven by single phase, linear DC motors. In the horizontal plane an air bearing guide system is used with separate stress frames for bearing pre-load forces. The elastically guided vertical z-axis has 4 mm stroke and is measuring in Abbe. It is thermally-, weight- and stiffness compensated and mounted statically determined on the x, y scale carrying beams. Compared to CMMs with a vertical air bearing guide system, the mass of the guides and their vertical drive offset was reduced significantly. A large improvement in system dynamics features a lowest eigenfrequency (rotation mode around the z-axis) of about 60 Hz. The uncertainty of a volumetric length measurement, due to residual geometric errors, will be about ± 20 nm.

## Introduction

To allow high speed scanning of MST products, small products in array set-ups and laboratory measurement tasks for calibration purposes of single objects, precision 3D coordinate measuring machines are highly flexible automated machines. Constant development of both touch probes<sup>5</sup> and machines<sup>2, 3, 4, 6</sup> is going on in industry and in research institutes. While the latter developments sometimes consists of “machine in machine”<sup>4</sup> set-ups where laser interferometry is used to realise extreme accuracy, industrial designs often use scales. This paper describes the machine layout of a scale based stand-alone design, aimed at an uncertainty of 25 nm in a 50×50×4 mm<sup>3</sup> volume. Figure 1 shows the schematic of the x y motion in top view.

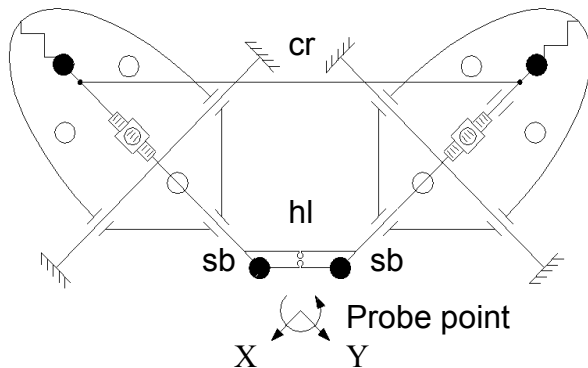
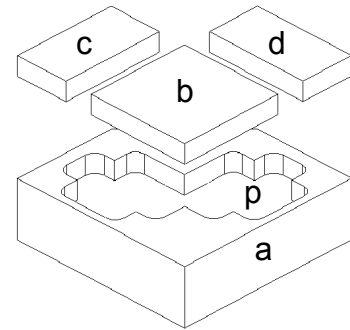


Figure 1: x, y system schematic top view

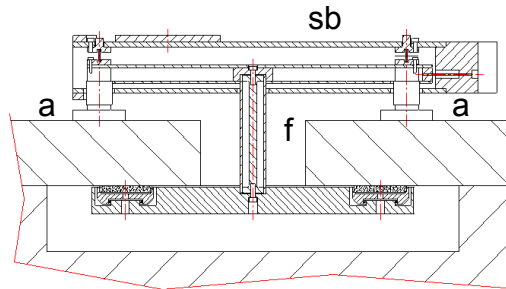
The x, y- system of figure 1 differs from that of [2] in that there are now four z-bearings (black dots), one at each end of a scale beam. The probe near end of the scale beams sb is connected by two hinged leaf springs hl (one visible, the other one below that). A connecting rod cr links the remote end of the scale beams. The internal degree of freedom avoids over constraint of four z-bearings.

## Description

The machine base consists of a base plate 2a (= a in figure 2) in which a pattern p with a depth of 50 mm is milled. Next three blocks (one square 2b and two rectangular 2c and d) are connected to the bottom plate. The moving parts (figure 3 and 4) are supported on the topsides of the three blocks 2 b c d. The bottom surfaces of the blocks, which overlap the pattern in the bottom plate, are used to pre-load the air bearings of the moving parts in z-direction.



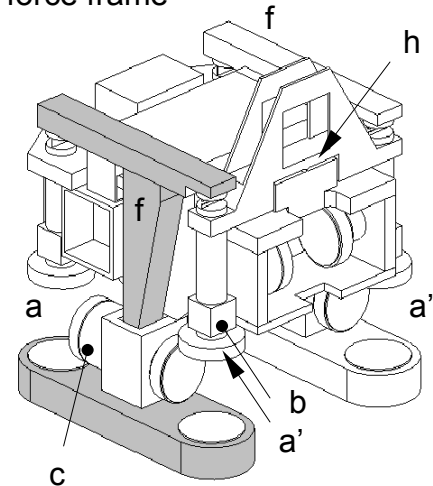
**Figure 2:** Machine-base



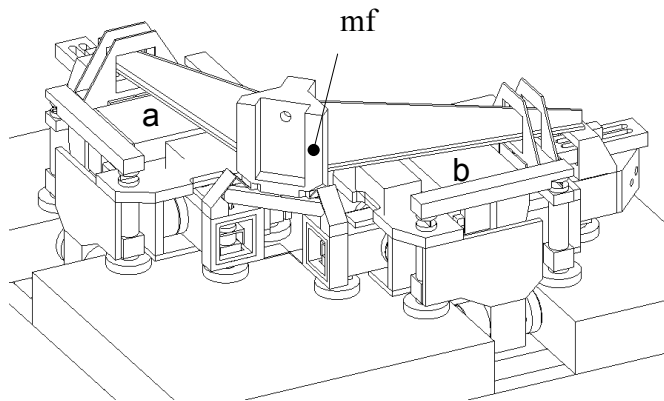
The pre-load is lead directly above the bearings 3a in z-direction of the moving bodies by one pre-load force frame 3f for a scale beam 3sb and two 4f for an intermediate body.

**Figure 3:** scale beam cross section with internal pre-load force frame

An intermediate body is equipped with four bearings 4a in z-direction. This made it possible to build low because the bearings in z-direction and their matching alignment bodies b can countersink into the moving bodies. The bearings in z-direction of an intermediate body, which are the most far from the probe a', are connected to the intermediate body with an elastic line hinge 4h to make sure that the support doesn't become over constrained. Two sides of the square block 2b function as an angle standard, guiding the air bearings 4c of the intermediate bodies.

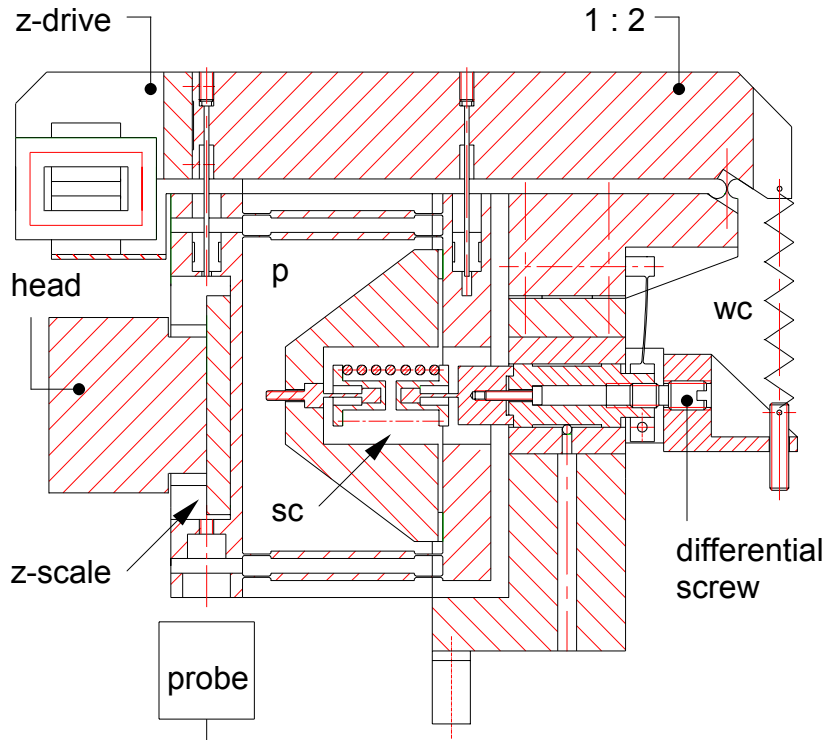


**Figure 4:** One of two intermediate bodies with statically determined mounted pre-load frames 4f



The mounting face mf, which carries the z-axis, is connected statically determined on the z-bearings of the x, y scale carrying beams (figure 5).

**Figure 5:** Mounting platform for z-axis statically determined on scale beam bearings to avoid bending



The z-axis is thermally- (by double parallelogram p), weight- (by weight compensation spring wc) and stiffness (by stiffness compensation spring sc) compensated. The probe and z-scale are aligned thereby measuring in Abbe.

**Figure 6:** The elastically guided vertical z-axis, 4 mm stroke, weight- and stiffness compensated, measuring in Abbe.

## Data summary

- Size of the Aluminum machine is about  $450 \times 450 \times 200 \text{ mm}^3$  supported on a base of about  $535 \times 535 \times 200 \text{ mm}^3$
- Thermal loop 150 mm
- Measurement loop 125 mm
- Mass of a scale beam is estimated to be 1,5 kg at a c.o.g. distance of 190 mm from the z-axis
- Mass of an intermediate body is estimated to be 4 kg at a c.o.g. distance of 190 mm from the z-axis
- Mass of the elastically guided z-axis is about 1,5 kg, moving mass: 0,12 kg
- Moment of inertia about the z-axis is estimated to be  $0,2 \text{ kg} \cdot \text{m}^2$
- Lowest eigenfrequency is about 60 Hz (rotation mode around the z-axis)
- Eigenfrequency of the probe in z-direction is about 180 Hz

## Error modeling

The procedure to map the geometric errors is almost the same as the one, which is described in [2] (page 62 to 104). There will be a small difference between the total error vectors of both machines because the guiding surfaces of this CMM are placed below the horizontal guiding surface.

The total error vector of the CMM results from the sum of the individual error vectors of the moving bodies of this CMM (Intermediate body A and B of figure 5, mounting face MF of figure 5 and z-mechanism Z of figure 6) and the squareness errors between the guide systems for x, y and z.

$$d\bar{P} = d\bar{P}_A + d\bar{P}_B + d\bar{P}_{MF} + d\bar{P}_Z + d\bar{P}_s + d\bar{P}$$

$$d\bar{P} = \left[ \begin{array}{c} {}_B T_x + {}_B R_y \cdot L_{\text{scale } x\text{-guiding surface}} + {}_{MF} T_x + {}_Z T_x + ({}_{MF} R_y + {}_x S_z) \cdot z \\ {}_A T_y - {}_A R_x \cdot L_{\text{scale } y\text{-guiding surface}} + {}_{MF} T_y + {}_Z T_y + {}_{Gb_A} S_{Gb_B} \cdot x - ({}_{MF} R_x - {}_y S_z) \cdot z \\ {}_{MF} T_z + {}_Z T_z \end{array} \right]$$

The errors in this vector are position dependent and can be calibrated and compensated with software. A realistic estimation of the expanded uncertainty ( $2\sigma$ ) of a length measurement is about:  $1 \text{ nm} + 1\text{E-}7 \cdot L$  (L is the measuring length in nm) and a realistic estimation of the expanded uncertainty of an angular measurement is about:  $0,05'' = 0,25 \mu\text{rad}$ . Estimations of the residual uncertainties after calibration of these thirteen errors are presented in table 6.1, in [7]. With this data the expanded uncertainty of a volumetric length measurement ( $2\sigma_{xyz}$ ), due to uncorrected residual geometric errors, will be about 20 nm.

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