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DESIGN AND VERIFICATION OF THE TRINANO ULTRA PRECISION CMM

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ABSTRACT

This paper describes the design and part of the verification experiments of a novel ultra precision coordinate measuring machine (CMM). The target uncertainty of this CMM is 100 nanometer (k=2) over its measurement range of 64 cubic centimeters. This is achieved using an innovative concept of which the workpiece table is supported by preloaded air bearings. An important aspect is the stability of the air gap which is measured at different positions in the measurement volume using three capacitive sensors, placed around the air bearing. It is shown that the variation of the air gap over a 60 minute interval has a standard deviation of 3 nm.

Index Terms **–** micro cmm, ultra precision, air bearings, kinematic design, nano metrology, thermal design, micro probe, precision engineering

1. INTRODUCTION

Most micro CMMs available today are the result of fundamental research. In general, it was the challenge to achieve the lowest possible uncertainty over a large measurement range. As a result the cost price of these CMMs is not an important factor. This limits technology adaptation in the industrial market. A market study confirmed that most owners of micro CMMs measure relatively small objects which fit in a matchbox. Furthermore, more than 70% of people interested in buying a micro CMM share this opinion. TriNano is precisely targeted at measuring those items with 100 nm uncertainty.

The first part of this article describes important considerations for designing a high precision metrology machine and how these considerations affect the design of the TriNano micro CMM as shown in figure 1. In the second part, measurements of the stability of the air gap between the air bearings and the moving workpiece table are presented. These measurements are performed on the machine to take all disturbances into account.

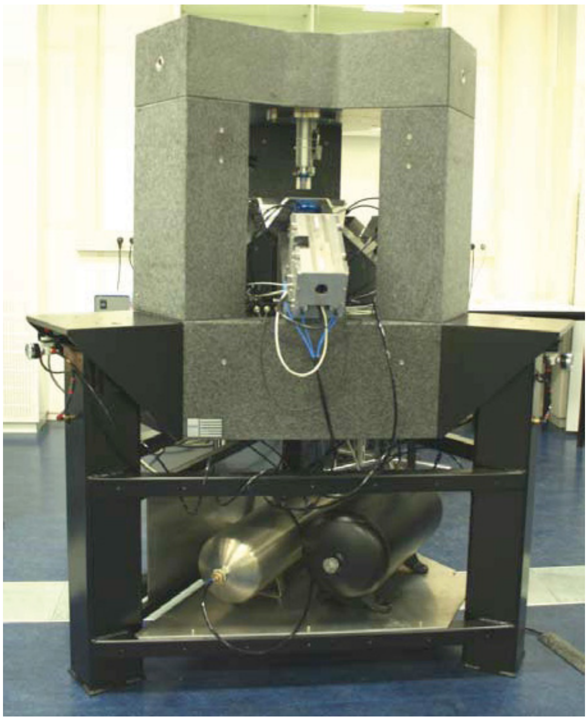

Figure 1. TriNano micro CMM.

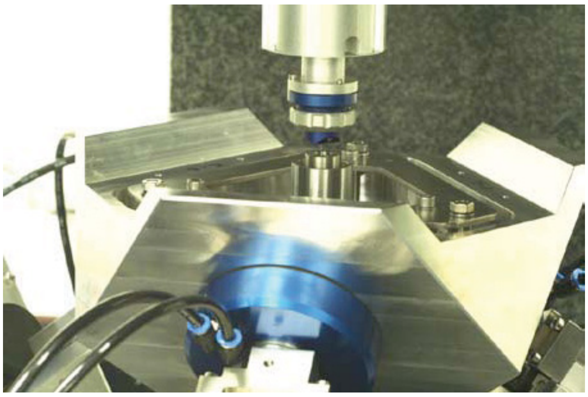

Figure 2. Moving workpiece table (aluminium dummy for testing purposes) supported by VPL air bearings.

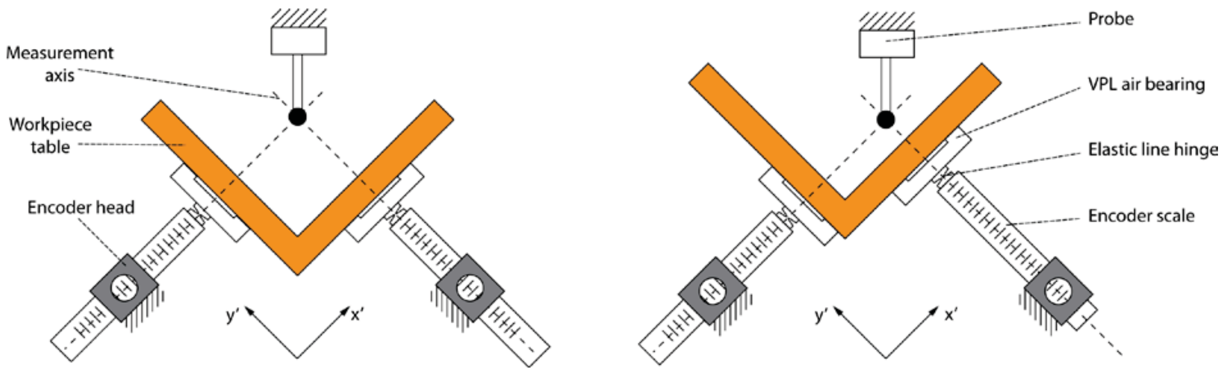

Figure 3. Schematic 2D operating principle, with the workpiece table in its neutral position (left) and after making a translation in local y'-direction (right).

2. OPERATING PRINCIPLE

In the TriNano, the workpiece moves in three directions with respect to the stationary probe by means of three identical linear translation stages as shown in figure 2. The stages are positioned orthogonally and in parallel and support the workpiece table via vacuum preloaded (VPL) porous air bearings as shown schematically in two dimensions in figure 3. From this figure the operating principle of the TriNano becomes clear. A linear translation of a stage is transferred via a VPL air bearing to the workpiece table. Translations of the workpiece table with respect to the linear stage in other directions than the translation of the stage are decoupled by the VPL air bearing. In this manner, the three stages independently determine the position of the workpiece table in three dimensions. Figure 4 shows a schematic 3D representation of the TriNano, the workpiece table, VPL air bearings and linear stages can be recognized.

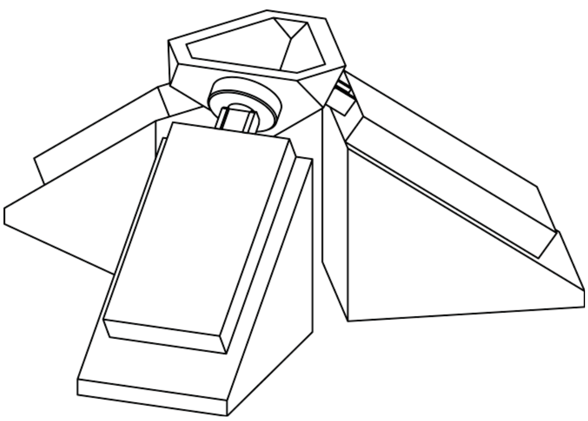

Figure 4. Schematic 3D representation TriNano

On each linear stage, the scale of an optical linear encoder is mounted. At the point of intersection of the measurement axes of these encoders the probe tip is located. As the orientation of the encoder scale does not vary with respect to the probe, as can be seen in figure 3, the TriNano complies with the Abbe principle over its entire measurement range. As a result, rotations of the workpiece table will have little effect on the measured dimension.

Instead of a conventional orientation of the machine axes, i.e. two orthogonal axes in the horizontal plane (x and y) and a third vertically oriented axis (z), the three axes in the TriNano are oriented such that each stage experiences an equal gravitational load. This orientation of the axes combined with the operating principle shown in figure 3, results in identical translation stages which can be produced at a lower cost.

The TriNano employs linear encoders to determine the position of the workpiece table. Compared to conventional ultra precision CMMs, which often employ laser interferometer systems; this principle results in a considerable cost reduction.

The parallel configuration of the three identical stages supporting the workpiece stages results in superior dynamic behaviour of the TriNano. This configuration allows a low and equal actuated moving mass of each stage with short and stiff structural loops. On machine measurements show that the lowest natural frequency in the positioning loop is 75 Hz. This allows a high control bandwidth required for scanning measurements of micro parts with a velocity of 1-2 mm/s.

3. KINEMATIC DESIGN

An unconstrained rigid body has six degrees of freedom (d.o.f.), three translations and three rotations. If all d.o.f. of a rigid body are fixed once, this body is said to be statically determined or exactly constrained. If more or less than six d.o.f. of a rigid body are constrained, it is said to be over or under constrained, respectively.

In order to obtain the highest measurement repeatability, exactly constrained designing is necessary [1]. Another important benefit of an exactly constrained design is that it will isolate critical parts or systems from the influence of manufacturing tolerances or deformations of the support frame, due to temperature variations or loading of the frame. An over constrained design often suffers from backlash and requires tight tolerances in order to function properly. The design of the TriNano is therefore based on well known kinematic design principles.

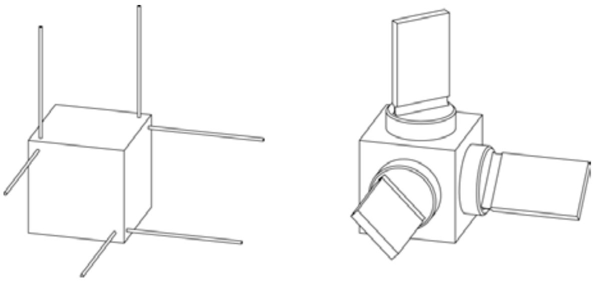

Figure 5. Exactly constrained design: classical (left), TriNano (right)

A classical solution of exactly constraining a body is to use six slender rods, as displayed on the left of figure 3. A single (VPL) air bearing as used in the TriNano, constrains 3 d.o.f.: 2 rotations and 1 translation. Applying an elastic line hinge releases one of the rotational constraints. Combining three of these air bearing-elastic line hinge combinations as shown on the right of figure 5 results in an exactly constrained workpiece table which allows repeatable positioning.

4. THERMAL DESIGN

Thermally induced errors are often the largest contribution to the total error budget in precision measurement equipment despite the research efforts performed on the matter [4]. However, certain straightforward measures can be taken to reduce these thermal induced errors, such as minimizing and controlling the heat flow and decreasing the thermal sensitivity of the machine.

In the Trinano, a pneumatic weight compensation system is applied to minimize the heat production in the actuators as represented in figure 6.

Figure 7. The housing of the TriNano insulates the measurement volume and the granite base frame from the environment.

Furthermore, a thermal insulating box is placed over the actuators preventing heat produced by the actuators from affecting the measurements. The volume in which the parts of the metrology loop are located is enclosed by a thermal insulation shield as shown in figure 7. A temperature control system can be employed to create a stable environment inside this volume. The thermal sensitivity of the TriNano is

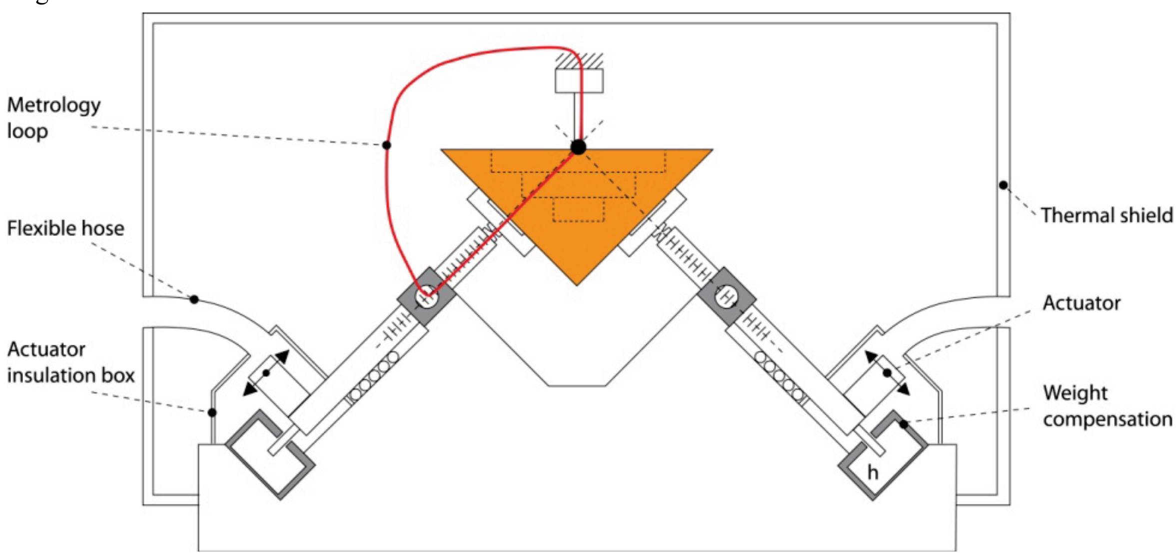

Figure 6. Schematic of the thermal design of the TriNano

further reduced by designing the parts of the metrology loop to have a large thermal time constant. For most parts this is achieved by adjusting their dimensions, instead of using expensive low thermal expansion materials. Only parts which need to be of a specific slender shape, such as the elastic line hinge, are made from a low expansion material.

5. GANNEN PROBING SYSTEMS

The TriNano is designed to be used with a wide range of sensors, including 3D probing systems, AFM-tips and white-light interferometers. In the standard configuration, the TriNano will be supplied with a Gannen XM probing system, as shown in figure 7. The Gannen XM is a 3D probing system supplied by Xpress Precision Engineering. It is suitable for measuring micrometer sized features with nanometer uncertainty. Other ultra-precision probes by Xpress will be supported as well, including the Gannen XP.

Figure 8. Gannen XM probing system.

The suspension of these Gannen probes consists of a silicon membrane with three slender rods as shown in figure 9. The probe tip is connected to the centre platform of this chip via a stylus. When the probe tip is displaced, the three slender rods will deform. This deformation is measured using piezo resistive strain gauges on the slender rods. The strain gauges are manufactured together with their electrical connections and the slender rods in a series of etching and deposition steps.

Figure 9. Chip and stylus of the Gannen XM probe with example products.

This results in a design with an extremely low moving mass of 25 mg including the weight of stylus and tip, as shown in figure 9. Also, it allows the manufacturing of rods with a thickness down to several micrometers, which as a result are very compliant. The stylus of the Gannen XP has a length of typically 6.8 mm. In this configuration an isotropic stiffness of 480 N/m is obtained and the sensitivity of the probe is similar in each probing direction.

Since the piezo resistive strain gauges are deposited onto the silicon membrane, hysteresis is below 0.05% and the standard deviation in repeatability is 2 nm over its whole measurement range and in any probing direction [5]. This combination of a highly compliant design with low moving mass and nanometer repeatability allows the use of micrometer sized probe tips. Currently tungsten probe tips with a diameter down to 42 µm have been manufactured and used with this probe, allowing 3D measurements on micrometer sized features [6].

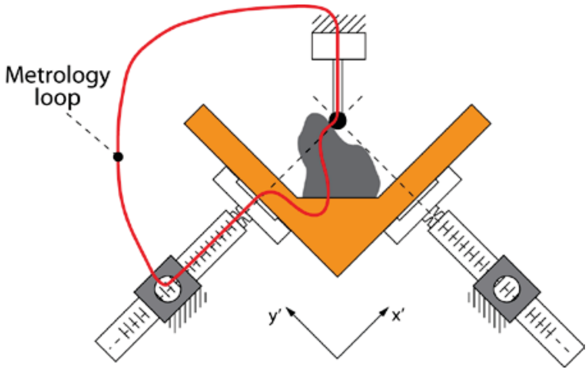

Figure 10. Metrology loop TriNano

6. VPL AIR BEARING

In figure 10, the 2D schematic of the TriNano is depicted in which the metrology loop is indicated. As can be seen, the loop passes through the encoder, the elastic line hinge, the VPL air bearing, the air gap, the workpiece table, the workpiece, the probe and back to the encoder via the granite frame. The fact that the layer of air of the air bearing is a part of the metrology loop might be cause for concerns, as is indicated in several prior studies [2,3]. To determine the effect of a VPL porous air bearing within the metrology loop on the performance of the TriNano, several tests have been performed.

7. VERIFICATION MEASUREMENTS

The stability of the air bearing has been verified on the machine to take all possible disturbances into account. During the conceptual phase of the TriNano development initial tests had already been performed to investigate the feasibility of the concept chosen as discussed by van Riel [7]. In addition to the stability at stand still, also the influence of a worktable translation is determined. This repeatability of the air gap height has been measured before and after translation cycles of the workpiece table.

Three capacitive sensors have been positioned around the air bearing using a ring as shown in figure 11. This setup allows the direct measurement of the axial displacement and tilt in two directions of the workpiece table relative to the air bearing. The direct measurement of the air gap behaviour contributes to the complete listing and characterisation of the disturbances which determine the total 3D uncertainty. The verification of the overall uncertainty is ongoing and the results will be published in the near future.

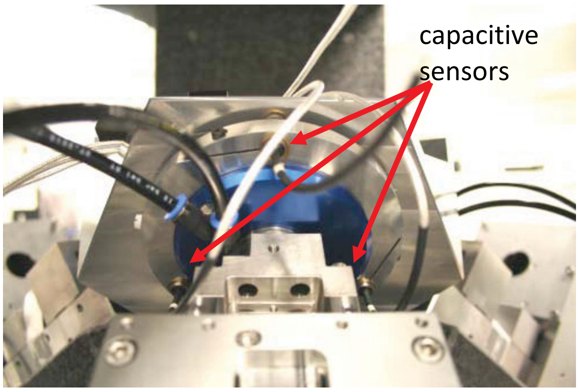

Figure 11. Test set-up to measure the air gap variation using 3 capacitive sensors.

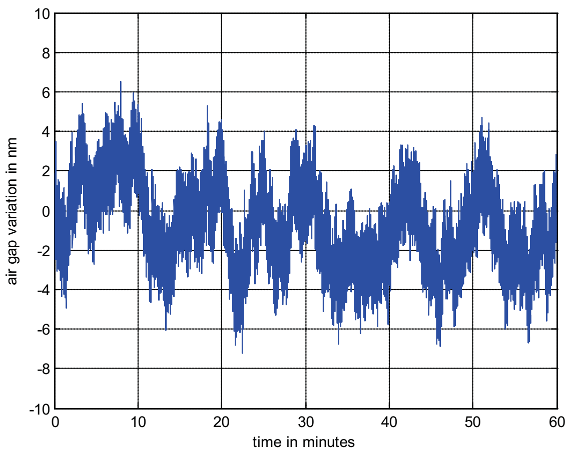

Figure 12. Axial air gap variation over a 1 hour time frame.

Figure 12 shows the result of a stability test over a 1 hour time frame. The standard deviation of the air gap variation is 3 nm. It can thus be concluded that the air bearings are not a limiting factor for achieving the specified 3D uncertainty of 100 nm. The variation of the air gap is caused by the variations of the vacuum pressure and supply pressure relative to the environmental pressure.
To determine the repeatability after movement of the workpiece table, the table has followed cycles of 10 mm displacements up and down at a travel velocity of 10 mm/s. No noticeable difference can be measured between the air gap before and after a cycle.

8. CONCLUSIONS

The design of the TriNano CMM presented in this paper has been realised and tests are being performed to characterise the machine behaviour like the dynamics and the overall uncertainty. One of the aspects which needed to be investigated is the air gap variation. It has been verified that during a typical measurement cycle, the contribution of the air gap to the uncertainty is about 3 nm (standard deviation) for a single axis in the configuration of TriNano CMM. It is thus shown, that these air bearings are not a limiting factor for TriNano to achieve a 3D measurement uncertainty of 100 nm.

INFORMATION

www.trinano.eu

JOINT DEVELOPMENT

TriNano is a joint development of Eindhoven University of Technology, NTS Systence, TASS Software Professionals and Xpress Precision Engineering. The project is partially funded by the European Regional Development Fund, the Dutch government and the province of Noord-Brabant under the OP South Netherlands program.

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