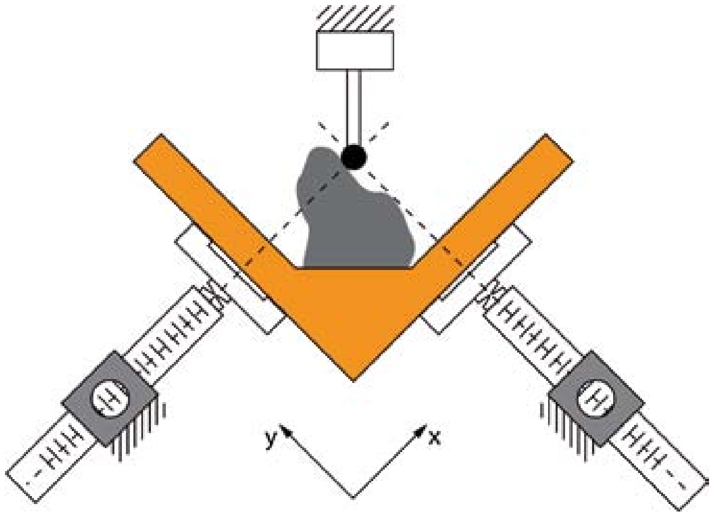
Nanometer uncertainty for a micro price

The TriNano, a new coordinate measuring machine (CMM), has been designed in line with needs from industrial and academic CMM users. Many of these users do not require a large measurement volume, but need nanometer uncertainty within a measurement volume of about 20-40 cm³. This reduction in measurement volume enables the TriNano to employ a new 3D actuation principle, resulting in a low-cost CMM with nanometer uncertainty.



• *Martijn van Riel and Ton Moers* •

Most micro CMMs available today are the result of fundamental research. In general, the real challenge is to achieve the lowest possible uncertainty over a large measurement range. Consequently, the cost price of these CMMs is often not the most important factor. This has resulted in wonderful metrology systems, but they often come at a high price. A market study conducted by the The Hague University of Applied Sciences showed that most owners of micro CMMs measure relatively small objects.

The micro manufacturing market is growing fast, with most of the products and their moulds fitting in a matchbox. The TriNano micro CMM is precisely targeted at measuring

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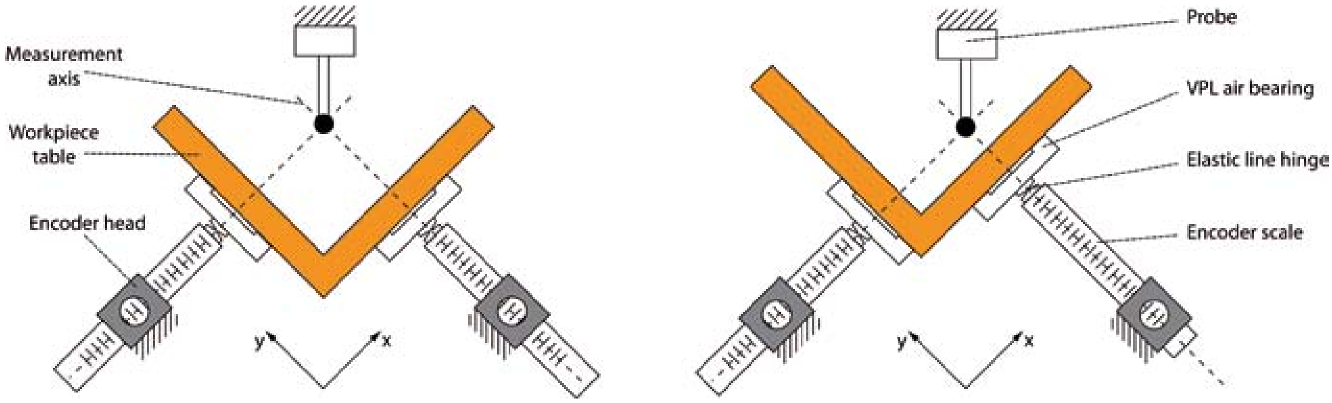


Figure 1. TriNano schematic 2D operating principle, with the workpiece table in its neutral position (left) and after making a translation in y direction (right).

those items with nanometer uncertainty. This article describes considerations for designing a high-precision metrology machine and their effect on the design of the TriNano.

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. 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 1. 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 2 shows a schematic 3D representation of the TriNano; the workpiece table, VPL air bearings and linear stages can be recognized.

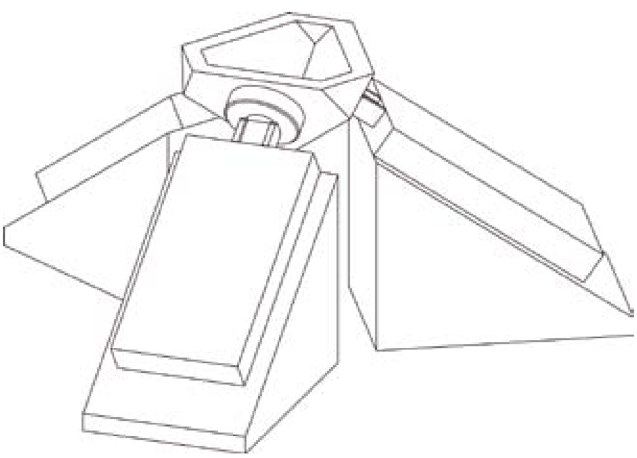


Figure 2. Schematic 3D representation of the TriNano.

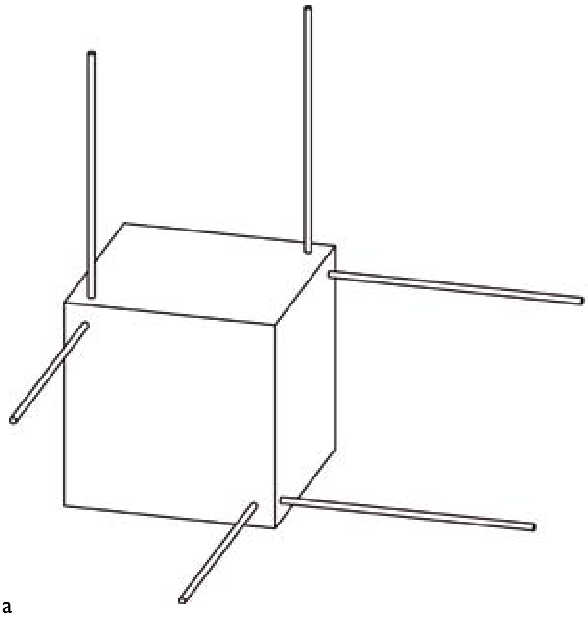
On each linear stage, the scale of an optical linear encoder is mounted. At the point of intersection of the measurement axes of these encoders the probe tip is located. As the orientation of the encoder scale does not vary with respect to the probe, as can be seen in Figure 1, the TriNano complies with 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 1, 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 results in a considerable reduction in cost. Finally, the TriNano is designed such that the use of expensive low-thermal-expansion materials can be kept to a minimum, thus reducing cost even further. As a result, a cost reduction of up to 75% compared to available high-precision CMMs can be achieved.

Kinematic design

An unconstrained rigid body has six Degrees of Freedom (DoFs), three translations and three rotations. If all DoFs of a rigid body are fixed once, this body is said to be statically determined or exactly constrained. If more or less than six DoFs of a rigid body are constrained, it is said to be over- or underconstrained, respectively.

An 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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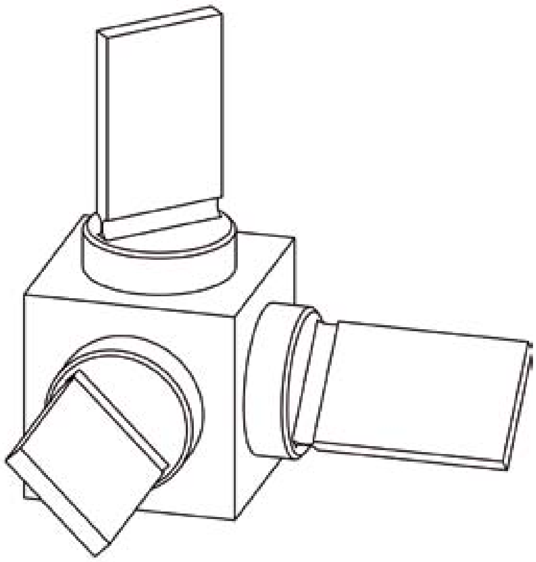
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Figure 3. Principle of an exactly constrained design.
(a) Classical.
(b) TriNano.

of the frame. An overconstrained design often suffers from backlash and requires tight tolerances in order to function properly. In order to obtain the highest measurement repeatability, an exactly constrained design is key [1]. The design of the TriNano is therefore based on well-known kinematic design principles, in order to obtain an exactly constrained design.

A classical solution of exactly constraining a body is to use six slender rods, as displayed in Figure 3a. A single (VPL) air bearing as used in the TriNano constrains three DoFs: two rotations and one translation. Applying an elastic line hinge releases one of the rotational constraints. Combining three of these air bearing-elastic line hinge combinations as shown in Figure 3b results in an exactly constrained body.

VPL air bearing

In Figure 4, the 2D schematic of the TriNano is depicted, with the metrology loop indicated. As can be seen, the loop passes through the encoder, elastic line hinge, VPL air bearing, including its air layer, workpiece table, workpiece, probe and back to the encoder via the frame. The fact that the air layer of the air bearing is a part of the metrology loop might be cause for concern, as has been indicated in several studies [2], [3]. To determine the effect of a VPL porous air bearing within the metrology loop on the performance of the TriNano, preliminary tests were performed and their results are shown in Figure 5.

The variation of the height of the air gap amounts to ± 8 nm over a period of 10 minutes, which includes sensor noise of ± 3 nm. It can be seen that the air gap variation

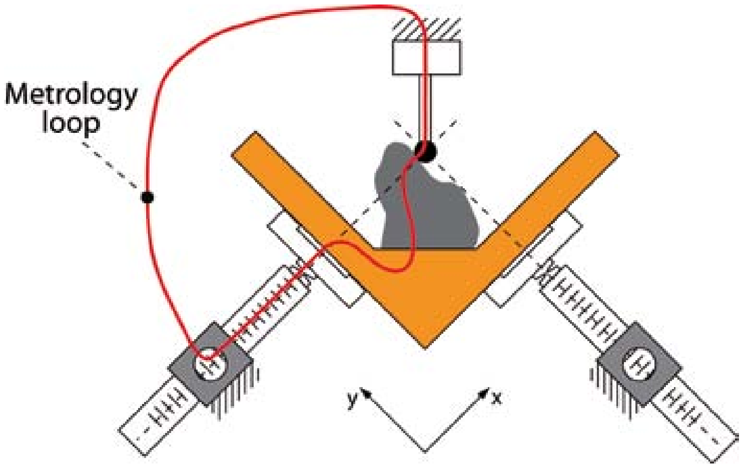

Figure 4. Metrology loop in the TriNano.

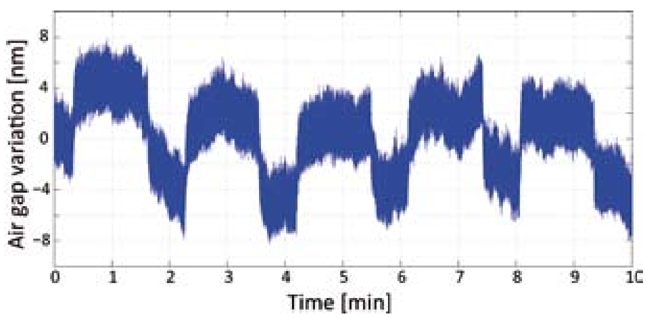

Figure 5. Air gap variation in a VPL air bearing.

displays a repetitive pattern with a cycle period of approximately two minutes. This cyclic behavior is due to variations in the pressure and vacuum supply. In the current test set-up, air pressure and vacuum were directly obtained from a wall outlet and no additional means were

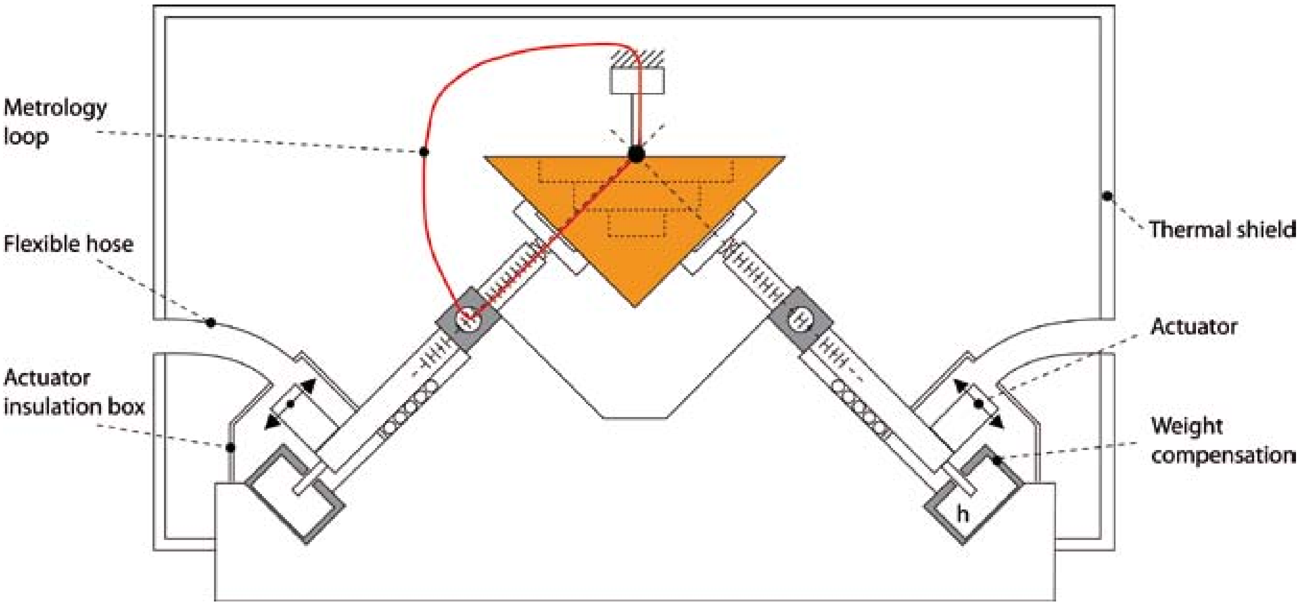

Figure 6. Schematic thermal design of the TriNano.

employed to control the vacuum and air pressure. Even without compensating for variations in air pressure and vacuum supply and for the environmental noise, the stability of the VPL air bearing is sufficient. Obviously, in the actual implementation of the VPL air bearings, pressure and vacuum monitoring and control will be applied to ensure stability.

Thermal design

Thermally induced errors are often the largest contribution to the total error budget in precision measurement equipment, despite more and more research performed on the matter [4]. However, certain straightforward measures can be taken to reduce these thermally 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. Furthermore, a thermally insulating box is placed over the actuators preventing heat produced by the actuators from affecting the measurement. The volume in which the parts of the metrology loop are located, is enclosed by a thermal insulation shield, as shown in Figure 6. A temperature control system is subsequently employed to create a ‘mini-environment’ inside this volume. The thermal sensitivity of the TriNano is 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 hinges, are made from a low-expansion material.

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 and probes from the Heimen series.

The suspension of these Gannen probes consists of a silicon membrane with three slender rods. The probe tip is connected to the center platform of this chip via a stylus. When the probe tip is displaced, the three slender rods, connected to the center platform in the silicon chip, 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 7. Gannen XM probing system.

Figure 8. Gannen probe chip with a selection of target products for measurement.

The resulting design has an extremely low moving mass of 25 mg including the weight of stylus and tip, as shown in Figure 8. Also, the design 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 equal 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 the 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].

The Gannen probes have been integrated on several commercial CMMs as well as on different custom set-ups for the high-precision measurement of small 3D components.

Joint development

TriNano is a joint development of Eindhoven University of Technology, NTS Systence, TASS Software Professionals and Xpress Precision Engineering, all based in the Netherlands. The first TriNano will be operational at the end of this year. The market has shown great interest in TriNano, both from industry and research institutes. In collaboration with a metrology equipment manufacturer, the TriNano will be launched in 2011 on a global scale.
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Information

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