Nanometre level uncertainty with

Coordinate measuring machines (CMMs) visualise a three-dimensional object by skimming it with a spherical tip on a thin needle. To do so, a CMM uses a sensor system that directly feeds back any contact between the tip and the object, enabling the machine to calculate the displacement of the tip in three dimensions. By skimming a product in this way, either by scanning or moving from point to point, the shape of the object can be reconstructed to a high degree of accuracy. The uncertainty of the measurement is currently limited by the accuracy of the available sensor systems. This article describes the redesign of a 3D measuring probe aimed at improving its assembly process and measurement uncertainty.

• *Edwin Bos* •

There is a growing demand for high-precision coordinate measuring machines (CMMs). An important application involves 3D measurements of micro-products, such as Micro Electro Mechanical Systems (MEMS). Examples include watch cogs or the fluid ducts found in inkjet heads or injection engines. High-precision probes have to be suitable for measuring these components.
This is why these CMMs need a tactile sensor system with an uncertainty level substantially below 100 nm (Pril, 2002). Various Ph.D. students in Eindhoven and Delft have worked on the development of high-precision CMMs (Vermeulen, 1999; Ruijl, 2001; Van Seggelen, 2007) and a number of them are now available on the market.
In 2003, a doctoral study was started at Eindhoven University of Technology entitled 'Automatische assemblage van hybride microcomponenten' (Automatic assembly of hybrid micro-components) (Bos, 2008). The study focused on the redesign of a 3D tactile sensor (Pril, 2002) with the aim of improving the assembly and the measuring accuracy. The new tactile sensor system was called Gannen XP.

How the system works

The first prototype of the silicon chip, which forms the heart of the Gannen XP tactile sensor system, is shown in Figure 1. The triangle in the middle of the chip can move relative to the outer edge using three small rods that are attached to the corners of the triangle. The deformation of the three rods is measured with piezo-resistive strain gauges attached to them.

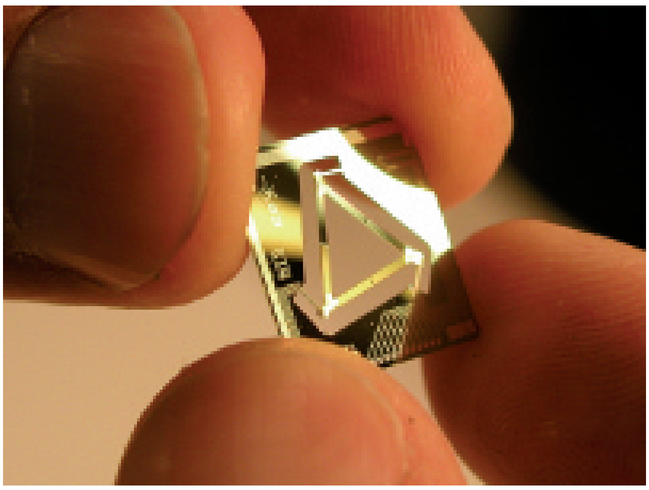

Figure 1. Prototype of the silicon chip that forms the heart of the Gannen XP.

the Gannen XP

Figure 2 shows one of the rods. The piezo-resistive strain gauges on the rod form a Wheatstone bridge, as shown in the diagram in Figure 3. When the probe tip is moved, two strain gauges are stretched (R_1 and R_2) and two strain gauges are compressed (R_3 and R_4). The Wheatstone bridge converts the resulting change in resistance into an electrical signal V_m.

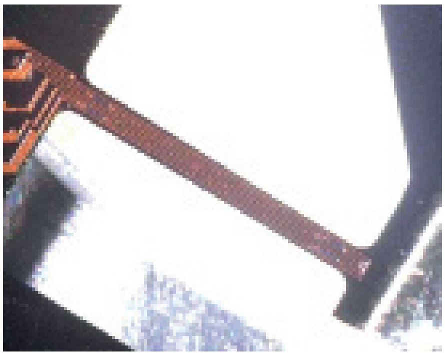

Figure 2. A rod in the prototype chip with four piezo-resistive strain gauges.

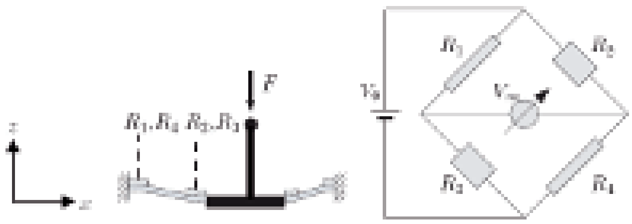

Figure 3. Diagram of how the probe works.

The probe tip is connected rigidly to the triangle in the middle of the chip by the stylus. This inner triangle is suspended on the outer edge by three rods, which fixate three of its degrees of freedom. As mentioned before, the probe receives a measurement signal from each rod. Using these three measurement signals, it is possible to calculate the remaining three degrees of freedom, thus determining the displacement of the probe tip.

High-precision measurements

The measurement uncertainty of the Gannen XP (see Figure 4) is determined with the aid of a calibration set-up in which the displacement of a measurement mirror is measured simultaneously by the probe and a laser interferometer. This makes it possible to compare the displacement as measured by the probe to the same displacement as measured by the laser.

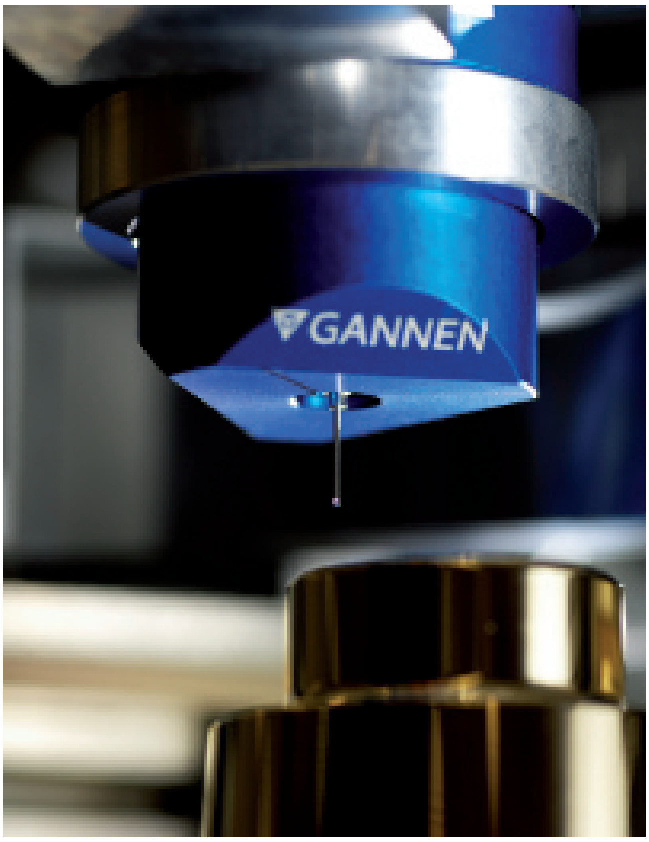

Figure 4. The Gannen XP on a high-precision coordinate measuring machine. (Photo: Bart van Overbeeke)

The deviation between the probe and the laser interferometer for a displacement in x, y and z direction is shown in Figure 5. For a period of 6 hours, the measurement mirror is moved back and forth 1,000 times over a distance of 5 micrometres in increments of 0.25 micrometres. The measured standard deviation between the probe and the laser interferometer is 2 nm at each measuring point for all directions.
A second important value is the drift of the probe, which is shown in Figure 6 for a 60-hour measurement without contact with an object. This figure shows that the contribution made by the electronics and thermal tension in the design is less than 2 nm in any 20-minute interval.

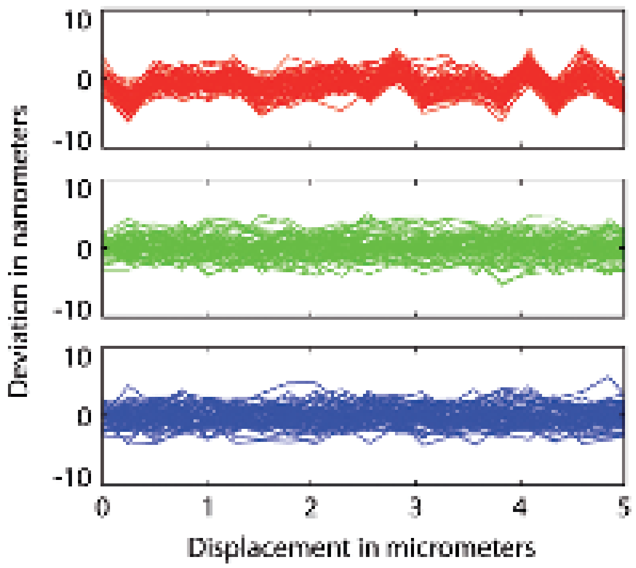

Figure 5. Measurement deviation of Gannen XP in the *x*, *y* and *z* direction compared to a laser interferometer over a displacement of 5 micrometres.

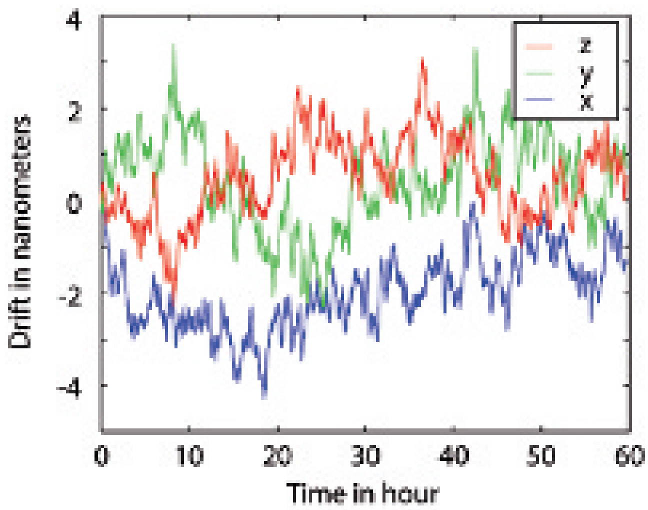

Figure 6. Drift of the Gannen XP measured over a period of 60 hours in a temperature-conditioned room.

The combined 3D uncertainty at twice the standard deviation ($k = 2$) of the Gannen XP is 50 nanometres. The Gannen XP is one of the most accurate 3D measuring probes on the market today. The main limitations are the compensation for unroundness and roughness of the probe tip. For the smaller tips in particular, with diameters of under 100 micrometres, it is still a major challenge to calibrate them and make them accurate enough.

An important advantage of the Gannen XP is that the probe's colliding mass and stiffness are extremely low, making it possible to avoid damaging products during the measurement. This damage influences the measurement and renders the often unique products unusable. This system can prevent these permanent deformations.

Measuring micro-components

The increasing miniaturisation of components, such as the parts in mobile telephones, sensors in cars, computers and medical equipment, create a growing demand for methods to measure them. That is why the Gannen XM was introduced at the end of 2007, 18 months after the launch of the Gannen XP. The Gannen XM is specially designed for 3D measurements of these micro-components (see Figure 7). It can be used with probe tips with a diameter of 50 micrometres, half the thickness of a hair, so the probe fits into minute openings and holes. The low stiffness and replacement costs and the possibility of using extremely small probe tips make the Gannen XM ideal for measuring micro-components and MEMS.

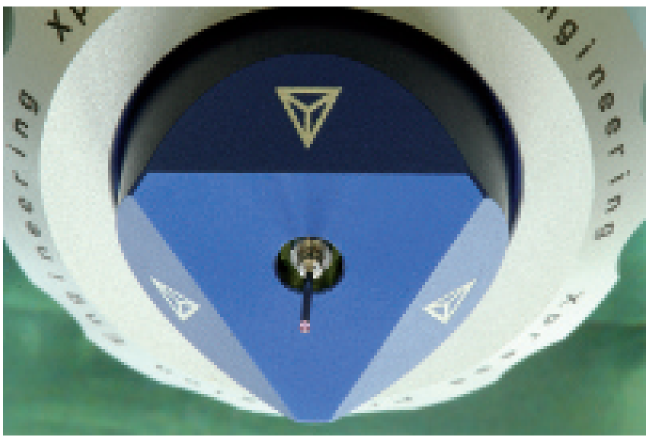

Figure 7. The Gannen XM, the second tactile sensor system produced by Xpress, was designed for 3D measurements of microproducts such as MEMS.

Influence of surface forces

Measurements with tactile sensors are influenced by surface forces consisting of electrostatic, hydrostatic and Van der

Waals forces. In order to measure with small tips without damaging the object, the contact forces between the probe tip and the object have to be reduced considerably. In the case of the Gannen XM, these forces are in the range of a few microNewtons. These contact forces, therefore, are in the same range as the surface forces between the probe tip and the object being measured.
This makes its possible to measure these forces with the probe when the probe tip is close enough to the object. Figure 8 shows that the object attracts the probe tip before there is any contact between them. From a certain distance, the surface forces are high enough to pull the probe tip to the object. This is called the 'snap-in' effect.

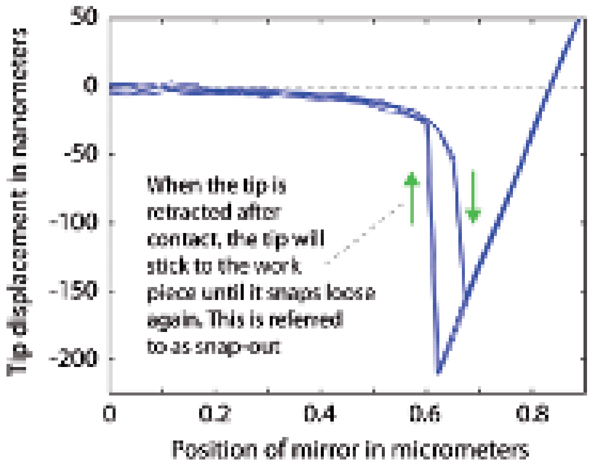

Figure 8: The influence of surface forces during a measurement.

Partnership

A number of companies worked on the research project and participated in the guiding committee, set up as part of the Innovation-driven Research Programme (IOP) for Precision Technology. As TNO Science and Industry's technology partner, C2V (Concept to Volume) supplied the silicon chip in the tactile sensor system. The assembly was completed in close co-operation with TNO Science and Industry. Other important contributions to the project came from NTS Mechatronica, Mitutoyo, NMi, Delft University of Technology, Heidenhain, IBS Precision Engineering, Hogeschool Utrecht (Utrecht University of Applied Sciences) and the Joint Technical Department (GTD) of Eindhoven University of Technology.

Xpress Precision Engineering

In 2004, shortly after starting on his doctoral research, Edwin Bos set up Xpress Precision Engineering. The main aim of the firm was to support research and strengthen working relations with the industry. The improvements in the area of assembly resulted in a considerable reduction in the cost price of the probe. In combination with an improvement in measuring behaviour, this led to further steps toward the commercialisation of the tactile measuring system called Gannen XP. Ernst Treffers joined the company, which has been a private limited liability company since 2007.
The Gannen XP is the first product to come from Xpress Precision Engineering. The name is based on the Japanese calendar, in which Gannen heralds a new era. 'As far as we are concerned, our product not only symbolises the start of our company, but also an entirely new measuring era', say Bos and Treffers.
June 2007 saw the final of New Venture 2007, a Dutch competition for new businesses initiated by McKinsey & Company. The New Venture jury, which consisted of (private) investors, companies and coaches, was hugely enthusiastic about the strategy and technological impact of Xpress. Of the 1,200 competitors, who submitted almost 500 business plans, Xpress was proclaimed the winner.
A second major development in that year was when Xpress was awarded a first- and second-phase Valorisation Grant by Technology Foundation STW. A committee consisting of investors, entrepreneurs and scientists chose Xpress from a number of proposals on the basis of technical and commercial potential, the business team and their planning.

www.xpresspe.com

Edwin Bos (left) and Ernst Treffers after winning the final of New Venture 2007.

Author's note

Edwin Bos was awarded his PhD on 8 April 2008 for the design of the Gannen XP at Eindhoven University of Technology (TU/e) and has been managing director of TU/e-spin-off Xpress Precision Engineering since 2004.

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