

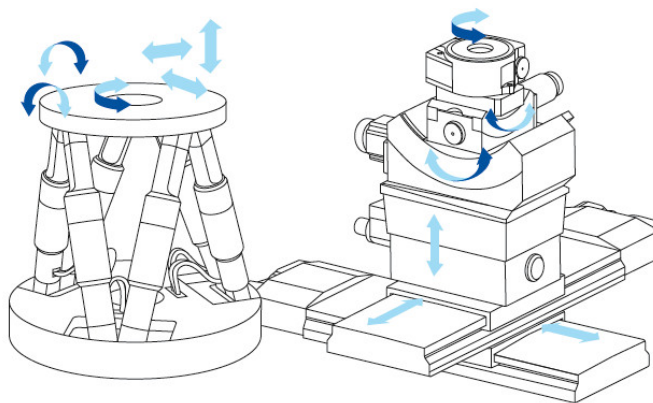
## Precise Positioning with Six Degrees of Freedom in Measurement Setups

Hexapods Help Measure Stress in a Model



Today many new and further developments would not be possible in the absence of computer-aided simulation processes. This is one of the reasons why the finite element method has become a standard tool in solid-state simulation. It can be used to calculate solutions to problems from a wide range of physical disciplines. Not only automobile manufacture, tool making and mechanical engineering, but also medical technology and the manufacturers of musical instruments can benefit from the results thus obtained. However, despite their simulation of reality, they can only provide calculated and thus fictitious values. This is why in particular for biomechanical and biomedical problems also hardware models are readily used for simulation.

Hexapods, which provide high-precision positioning with six degrees of freedom, offer interesting options for measurement setups used to test how well the models reproduce reality. Hexapods have a parallel kinematic structure, i. e. six drives act together on a single moving platform (Fig. 1).



*Fig. 1 Hexapods are parallel-kinematic systems (a). Their design is much more compact than that of serially stacked multi-axis systems (b), and their moving mass is much lower (Image: PI)*

Depending on their design, Hexapods can position loads from a few kg to several tons with high precision in any spatial orientation in three linear and three rotational axes. The best-known application of six-axis parallel-kinematic systems are probably flight simulators. Hexapods, suitable for applications in metrology, industry or research, are however much more accurate.

Depending on the requirements of the application, they are driven by high-precision drive screws and precisely controllable DC motors or directly by linear motors, e. g. based on piezo actuators, instead of using hydraulic drives.

Their advantages compared with serial, i.e. stacked systems, are that they have much better path accuracy, repeatability and flatness. In addition, the moved mass is low, enabling better dynamic performance, which is the same for all motion axes. Moreover, cable management is no longer an issue, because cables are not moved, and, last but not least, the system features a much more compact design. Nowadays a wide range of applications benefit from these advantages. These applications range from metrology and mechanical engineering to medical technology and research. For the latter, dentistry provides a recent example:

## Adaptation of Orthodontic Apparatuses

In orthodontics, the behavior of the tooth elastically embedded in the bone must be investigated, for example, for corrective measures. To simulate realistic tooth motions using an experimental setup directly on the patient is, however, hardly feasible. Such an "in vivo" experiment would be highly unpleasant for the patient or test person. Moreover, the anatomic conditions in the oral cavity are rather unsuitable for investigations and tests that allow verifiable statements regarding the active force system in tooth motions.

Nevertheless, the question that always needs to be answered is which forces and torques occur and in which magnitude. This is where simulations using the finite element method can provide answers. However, in practice they have only had limited success, because, due to the complex generation of suitable FE models, the values calculated by computer are unfortunately always fictitious. Thus, for example, the calculation of the biomechanical behavior of the connective tissue of the periodontal ligament (PDL) has not yet provided a clear solution.

## Realistic Simulations Using a Model

This is why scientists from the University of Ulm have used a different approach and developed a new solution, designed to answer the question how the tooth embedded elastically in the jawbone behaves under stress. The result is a numerically controlled experimental setup that allows measurements of the clinically relevant forces acting on the tooth during the orthodontic tooth motion. In this way, FE models can be checked and modified on the basis of real measurements.

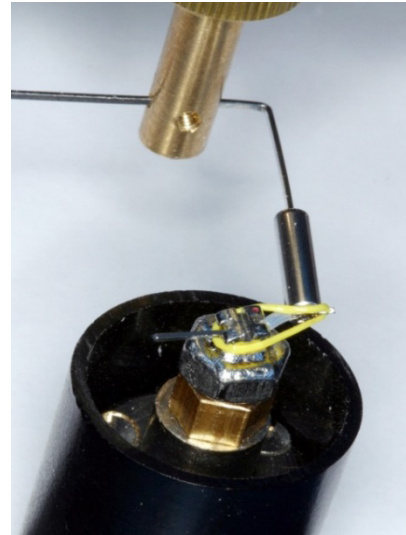
The biomechanical structure of the simulation system is based on a parallel-kinematic Hexapod (Fig. 2) from the extensive product range of PI (Physik Instrumente).



*Fig. 2 The biomechanical structure of the simulation system is based on a parallel-kinematic Hexapod of series H-850 (Image: PI)*

At a diameter of 348 mm and a height of 328 mm, the Hexapod has a very compact design. At a repeatability of  $\pm 1 \mu\text{m}$  (Z axis) and  $\pm 2 \mu\text{m}$  (X and Y axes) and thanks to the high stiffness of the overall system, this system turns out to be the ideal solution for simulating the small motions of a tooth in the jawbone. In addition to that, its pivot point inside and outside the tooth root can be freely defined, a necessary prerequisite for biomechanical simulation.

For simulation, the Hexapod was combined with a force sensor mounted on a rigid rotary table. The phantom tooth (Fig. 3), essentially an orthodontic bracket like that on a human tooth, is mounted directly at the sensor.



*Fig. 3 The force sensor is mounted on the top platform of the Hexapod. It simulates a real tooth and registers the forces and torques acting there. The platform is controlled by an especially developed algorithm that simulates the elastic behavior of the periodontal ligament (Image: University of Ulm)*

The standardized elastic behavior of the periodontal ligament is simulated by means of a program especially developed for this purpose. The forces and torques generated by the orthodontic apparatus to be studied act on the phantom tooth via the orthodontic bracket.

The Hexapod moves the test specimen in small steps, in order to measure the different stresses, depending on the tooth position. The required commanding of the Hexapod system is very easy. The digital Hexapod controller allows the user to set a pivot point as the center of rotation anywhere inside or outside the Hexapod work space. This freely definable pivot point is maintained, independently of the motion.

The user specifies all motion commands in Cartesian coordinates, whereas all transformations to the individual drives are performed by the controller.

Thanks to the high positioning accuracy, the force applied to the specimen can be exactly assigned to a position, allowing the stress points at the tooth to be accurately determined (Fig. 4). The high stiffness of the Hexapod ensures a real simulation of the tooth motion.



*Fig. 4 The tooth reconstructed from radiological data is embedded in the red-colored periodontal ligament (shown without the bone). The loads act on the points shown in the middle portion of the tooth crown as yellow spheres (image: University of Ulm)*

The results obtained with the simulation model thus contribute to a better evaluation of orthodontic processes in the oral cavity and a more effective design of corrective measures. Similar results can also be achieved in other areas, for example in dental and hip implants or the like, using suitable test setups. Thanks to the versatility and large number of variants of parallel-kinematic Hexapods, industrial applications are also possible.

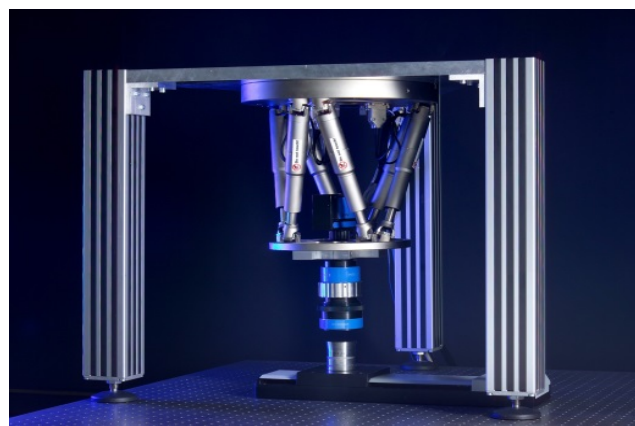
## Ultraprecise Measurement System for Optical Surfaces

Mold inserts used for manufacturing optical lenses place extreme demands on the accuracy of the test methods. Interferometric measuring equipment can now be used to automate these requirements and integrate them directly into production. Here, too, high-precision Hexapods have found a typical area of application:

For optimum measurement of both plane as well as spherical and aspherical test specimens, the positioning of the interferometer requires five degrees of freedom: The interferometer must travel in the direction of the x, y and z axes.

For orientation perpendicular to the test axis, additional rotation around the x and y axes and, in the case of cylindrical lenses, also around the z axis is required. The Hexapod that is in charge of positioning tasks is mounted on 20-mm thick aluminum plate.

The interferometer located inside the Hexapod does not interfere with its motion. The CCD camera takes the picture. It is digitized, saved in the computer and evaluated. A control program written in MatLab sends suitable control commands to the Hexapod.



*Fig. 5 Ultraprecise measurement system for optical surfaces In this application, too, Hexapods are the method of choice (Image: PI / Fraunhofer Institute for Production Technology IPT)*

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## About PI (Physik Instrumente)

In the past four decades, PI (Physik Instrumente) with headquarters in Karlsruhe, Germany has become the leading manufacturer of nanopositioning systems with accuracies in the nanometer range. With four company sites in Germany and ten sales and service offices abroad, the privately managed company operates globally. Over 700 highly qualified employees around the world enable the PI Group to meet almost any requirement in the field of innovative precision positioning technology. All key technologies are developed in-house. This allows the company to control every step of the process, from design right down to shipment: precision mechanics and electronics as well as position sensors. The required piezoceramic elements are manufactured by our subsidiary PI Ceramic in Lederhose, Germany, one of the global leaders for piezo actuator and sensor products. PI miCos GmbH in Eschbach near Freiburg, Germany, is a specialist for positioning systems for ultrahigh vacuum applications as well as parallel-kinematic positioning systems with six degrees of freedom and custom-made designs.



*PI headquarters in Karlsruhe, Germany: More than 350 employees work on high-resolution drive systems and positioning systems*