Piezomotors:

A novel type of piezoelectric motor has been developed at the Department of Mechanical Engineering of the Katholieke Universiteit Leuven, Belgium. This 'Leuven motor' can operate in several drive modes by virtue of an innovative symmetrical design. Case studies show that the Leuven motor can be used as a core component of a new generation of stiff, compact and non-magnetic positioning systems with a high positioning resolution, wide speed range and a large stroke, capable of operating in demanding environments, e.g. cryogenic and (ultra-high) vacuum.

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Product design and production technology in general show a strong trend towards miniaturization. Sophisticated positioning devices that realize a controlled motion on a submicron level and beyond act as an enabling technology to realize this evolution. Examples of these devices are found in high quality consumer goods (e.g. data storage devices and auto-focus mechanisms for cameras), production machines (e.g. wafer steppers and fast-tool servos), inspection machines (e.g. high-resolution optical microscopes, electron microscopes and surface-profiling tools) and medical instruments (e.g. robotic surgery and tomography).

To understand the evolution of the requirements for positioning devices, the semi-conductor sector can be seen as the leading industry. The technical evolution in this industry is well illustrated by the steady reduction of the line thickness in central processing units. Figure 1 shows an exponential decrease, as predicted by the famous Law of Moore [1]. According to this law, the number of transistors that can be placed at a reasonable price on an integrated circuit increases exponentially in time.

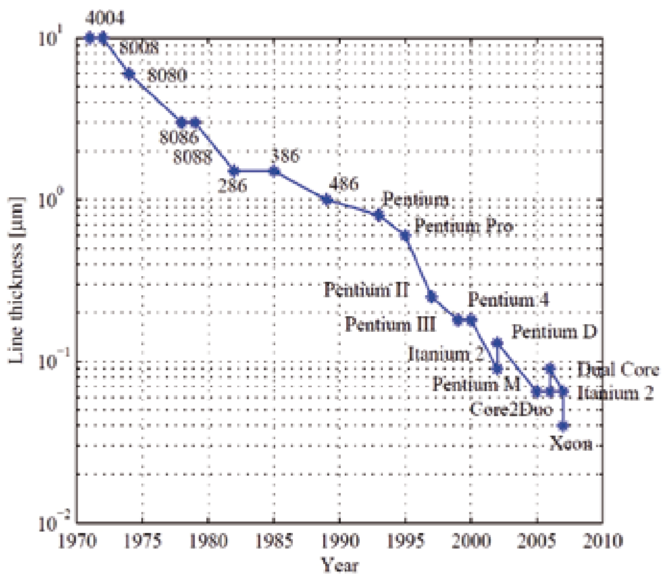


Figure 1. Evolution of the circuit line thickness of Intel processors (data collected from www.intel.com).

an enabling technology

The decrease in line thickness is realized by the evolution of lithography machines. These machines pattern tiny circuits on silicon substrates by exposure to light. Since the construction of lithography machines involves highly accurate lenses, positioning frames, etc., the evolution in line thickness leads to more stringent requirements for precision production machines. Consequently, the evolution of ultra-precise production machines (e.g. diamond turning, micro EDM, micro milling, ELID grinding) follows the pace of the evolution of lithography machines. Taniguchi [2] showed this trend towards higher machining accuracy in his famous graph, depicted by solid curves in Figure 2. However, these curves do not include an economic constraint, while Moore states that the increase in number of transistors is realized *at a reasonable cost*. This cost constraint can be added by a time constraint: the machining time does not increase with increasing precision. This criterion sets two extra requirements for ultra-precise positioning systems: (i) the positioning speed must remain constant, and (ii) the bandwidth must increase [3]. These requirements can be incorporated into an 'extended Taniguchi graph', as shown by the dashed curves in Figure 2.

Figure 2 thus allows extracting specifications for novel ultra-high precision machines: a total machine accuracy of at least 1 nm, and a total stiffness of over 40 N/μm. Moreover, a large travel is needed (over 100 mm) and, to keep machining time down, a high velocity mode with a speed higher than 100 mm/s is required.

Piezoceramic actuators are appropriate candidates to fulfill these specifications [4]. They show a quasi unlimited resolution, possess a high force density and have a short response time. Especially in nanotechnology, piezoceramic actuators offer two key properties that distinguish them from other driving technologies: inherent vacuum compatibility and absence of electromagnetic interference. For this reason, piezoceramic actuators are chosen as actuators for a novel linear piezoelectric motor that has to meet the above mentioned specifications. This motor is called the 'Leuven motor'. The Leuven motor can be used as a core component for a new generation of positioning systems. This article describes the design and the performance of the motor, as well as its implementation into two positioning systems.

Mechanical design

Figure 3 shows a schematic drawing and a photograph of the Leuven motor. It consists of a metal structure, called stator, which is preloaded against a slider at a contact point. The piezoceramic actuators (P1-P4) are mounted inside the stator in such a way that they directly contribute to the stiffness of the Leuven motor. Elastic hinges connect the piezoceramic actuators to the fixed frame and the contact point. A tuning block is connected to the stator via leaf

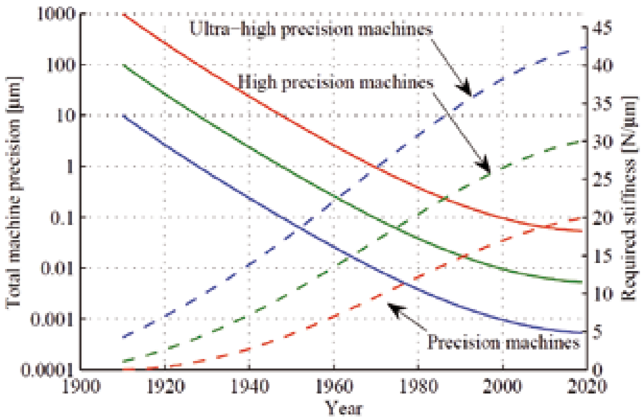


Figure 2. Taniguchi curves (solid lines) and extended Taniguchi curves (dashed lines) to describe trends for required machine accuracy and stiffness.

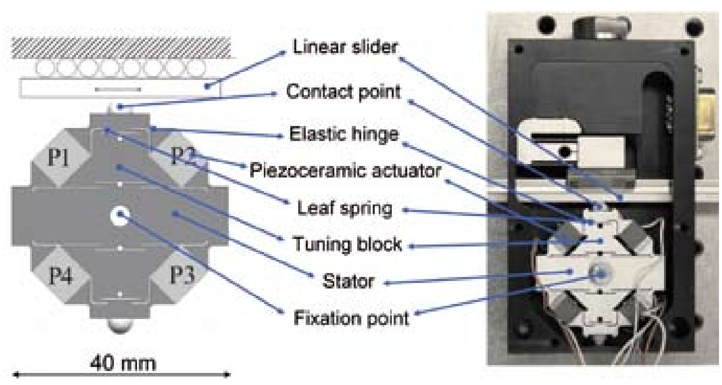


Figure 3. Schematic drawing and photograph of the linear piezoelectric Leuven motor.

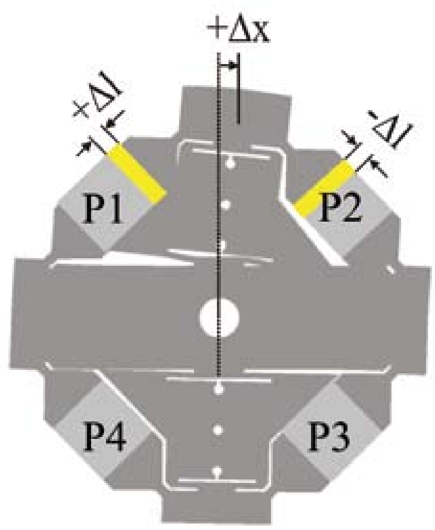


Figure 4. Working principle of the Leuven motor in the direct-drive mode. In this mode, the motor basically imitates piezostack performance.

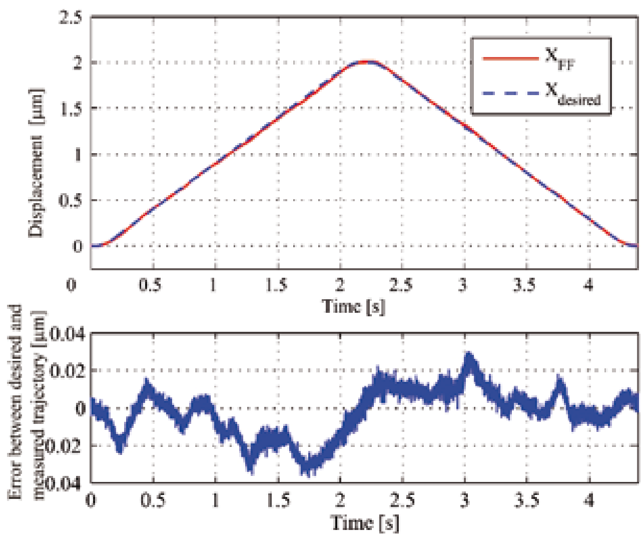


Figure 5. Comparison between measured, open-loop slider displacement and desired displacement for tracking a 1 μm/s trajectory with the direct-drive mode (top). The bottom plot shows the error between desired and measured trajectory.

springs. A bolt connects the stator to a fixed frame at the central point of symmetry.

By applying voltages to the piezoceramic actuators, the drive point shifts and moves the slider by friction. The Leuven motor offers three distinctive operational modes which enable it to drive the slider in a wide speed and accuracy range. The nature of the applied voltages determines which operational mode is active. Principle and performance of each mode is described next.

Performance

Direct-drive mode

The direct-drive mode inherits the advantages of a piezoelectric ceramic: it aims for high positioning resolution and high stiffness. Figure 4 illustrates the working principle. A positive voltage is applied to piezoceramic actuator 1 (P1) and a negative voltage is applied to piezoceramic actuator 2 (P2). The respective piezoceramic actuators are thereby elongated or contracted over a distance Δl. The contact point moves to the right over a distance Δx. If the slider is preloaded to the Leuven motor and the Leuven motor is rigidly attached to a fixed reference, the slider will also move with a distance Δx, supposing no slip. The maximum stroke is limited to a few μm, since it directly relates to the stroke of the piezoceramic actuators.

- Open-loop results
  As is shown by Figure 5, accurate open-loop control can be achieved by identifying a feed-forward system model, and compensating the hysteresis of the piezoceramic actuators. A continuous triangular trajectory with a speed of 1 μm/s is applied. The maximum error is ± 30 nm.

- Closed-loop results
  Closed-loop position control offers both an improved tracking behavior and stability of this tracking behavior in time compared to open-loop control. Figure 6 illustrates the control architecture.
  Figure 7 shows an example of the tracking behavior for a speed of 2 μm/s. The tracking error now remains within the sensor noise, which is a band of about 10 nm.

Resonant-drive mode

For applications requiring a large stroke and high velocity, the resonant operation mode can be used. This principle is based on the generation of an ultrasonic and thus silent elliptical motion of the contact point to drive a slider through a friction interface. This oscillation of the contact point results in a net macroscopic motion of the slider if

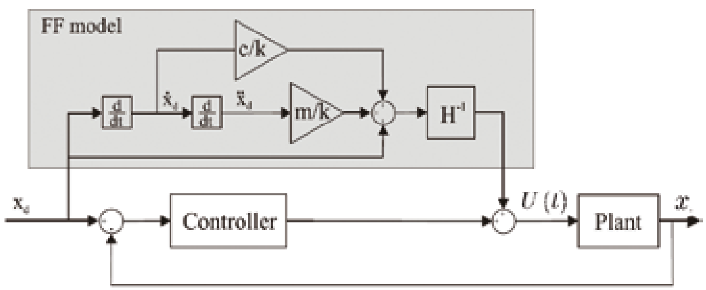


Figure 6. Schematic diagram of the controller for the direct-drive mode.

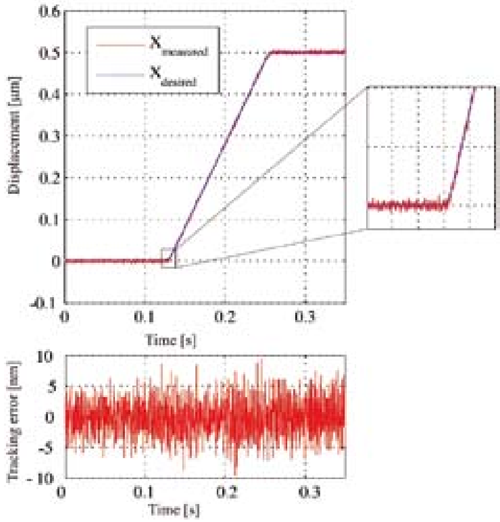


Figure 7. Example of trajectory tracking in closed loop using the direct-drive mode. The bottom plot shows the tracking error in nanometre scale.

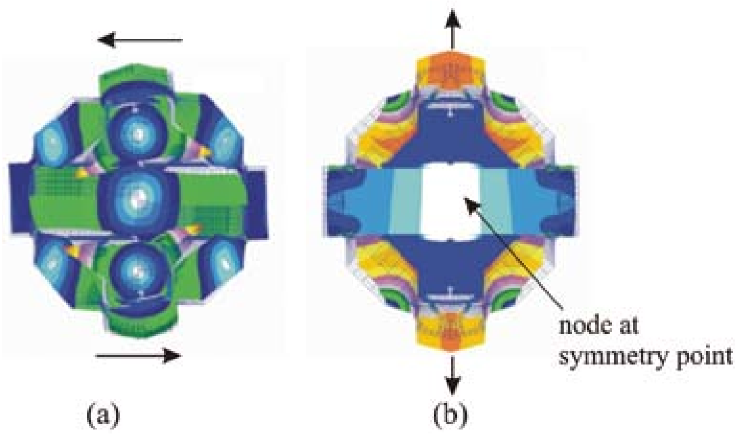


Figure 8. Finite-element calculation of the horizontal (a) and vertical (b) eigenmode of the Leuven motor. Notice the oscillation of the tuning blocks in (a), while hardly any oscillation is noticed in (b).

(i) the drive frequency is high enough, and (ii) a net friction force is present in the positive or negative direction.

To optimize the drive speed and traction force of the slider, respectively, the horizontal and vertical oscillation amplitudes of the elliptical motion of the contact point should be maximized. This is achieved by operating the stator in resonance. Figure 8 shows the results of a finite-element calculation of the horizontal and the vertical eigenmodes of the Leuven motor. Optimal efficiency is achieved when these two eigenmodes coincide. This can be done by altering the tuning mass shown in Figure 3 to compensate for modeling, production and assembly errors. Figure 9 shows how both eigenmodes shift in response to changing this mass.

The importance of tuning is illustrated by open-loop force-speed measurements in Figure 10. A maximum driving speed of over 300 mm/s and a stall force of 12 N are achieved. Careful adaptation of the tuning mass doubles both the maximum driving speed and the stall force in comparison with the same motor right after the production and assembly process.

Figure 11 finally shows the results of a closed-loop position-tracking experiment. To minimize non-linear behavior, a dedicated control strategy is designed. This strategy dramatically decreases the required complexity of the controller. A triangular trajectory with a maximum slider speed of 1 μm/s is applied. The position is measured with a laser interferometer with a resolution of 80 nm. The zoom on the right shows that the reference trajectory is followed within the resolution of the interferometer. A lead-lag controller was used.

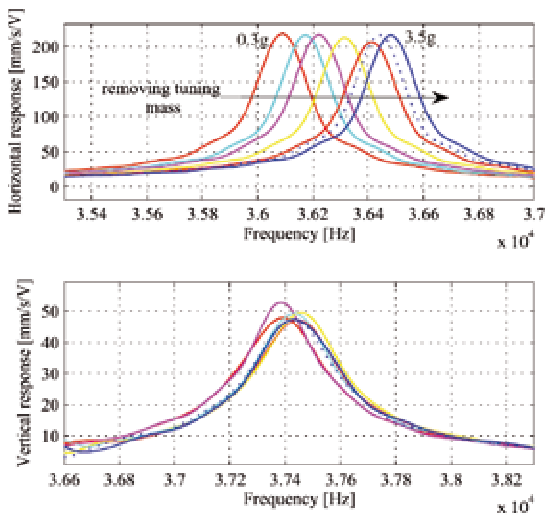


Figure 9. Variation of the horizontal (above) and vertical (below) eigenmode when changing the tuning mass.

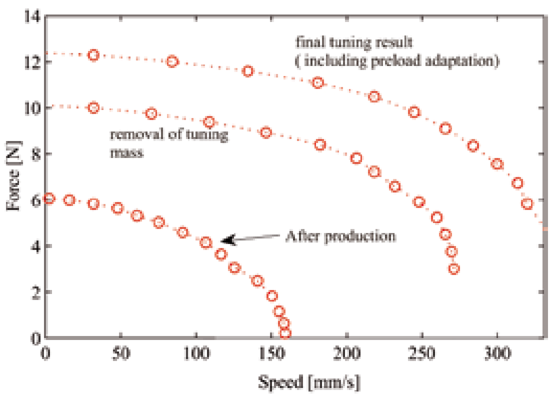


Figure 10. Influence of tuning on the traction-speed characteristic of the Leuven motor.

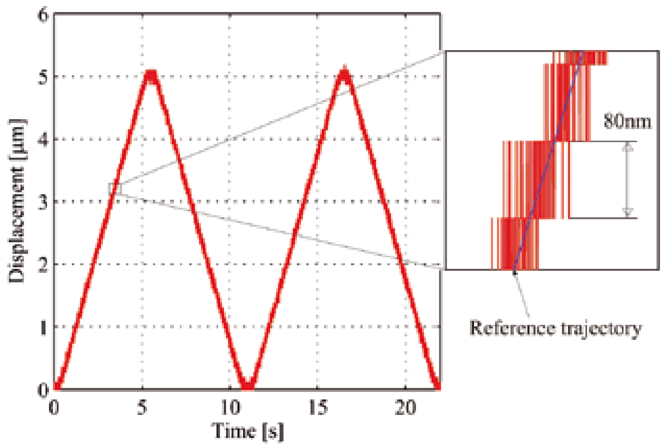


Figure 11. Tracking performance in the resonant-drive mode for a speed of 1 µm/s when a lead-lag controller is implemented.

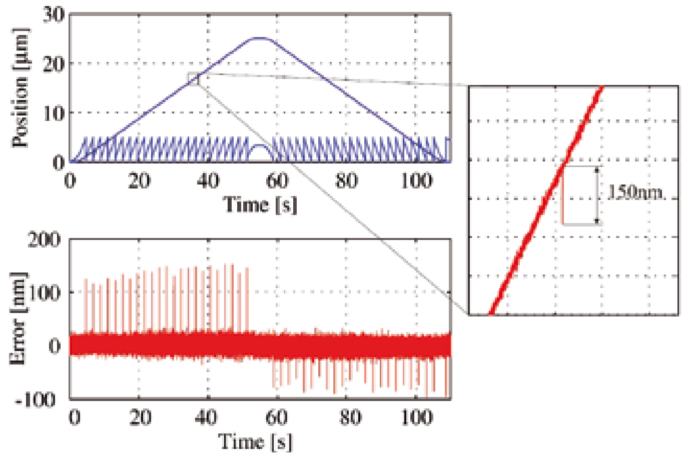


Figure 13. Experimental example of trajectory tracking with the pulse-drive mode.

Pulse-drive mode

The maximum travel for the direct-drive mode equals about 5 µm. Many industrial applications require a much larger displacement, ranging from a few mm to several hundreds of mm. This large displacement range can be obtained by the application of the resonant-drive mode. However, the maximum resolution obtained in this drive mode is limited to 40 nm p-p. Therefore, an alternative operation mode, denominated as pulse-drive mode, is explored. This driving method sometimes is referred to as inertial drive mode [5] or stick-slip drive mode [6].

Figure 12 illustrates the working principle of the pulse-drive mode. A sketch of the driving cycle is given on the right,

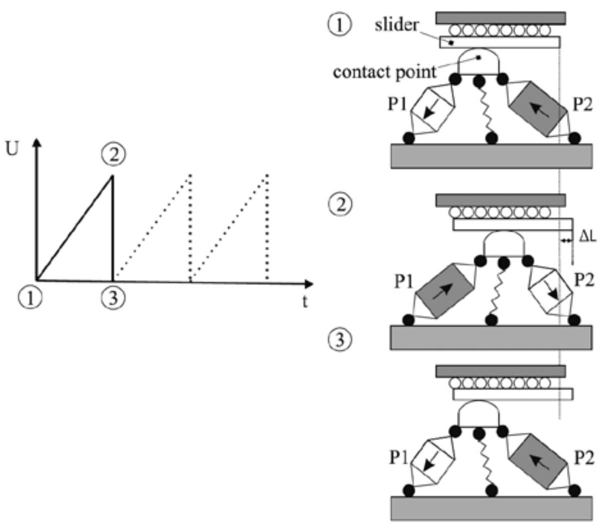


Figure 12. Working principle of the pulse-drive mode.

while the applied voltage to one of the piezoceramic actuators is shown on the left. The voltage *U* represents the voltage applied to the piezoceramic actuators P1 and P2. As the driving saw-tooth signal *U* goes up slowly, the slider sticks to the contact point and moves to the right over a distance Δ*L*. When the driving signal U suddenly drops, the contact point retracts and slips to its original position. At the end of this cycle the slider has made one step Δ*L*. By repeating this, large strokes are obtained.

Figure 13 shows an experiment where the motor is used for tracking a function with a stroke of 25 µm at a speed of 0.5 µm/s. The saw-tooth signal generated at the input of the piezoceramic actuators is also shown. The control architecture is similar to the one in Figure 6. The zoom window at the right of the figure indicates good tracking behavior except for the short spikes generated during the retraction period. These spikes can be as large as 150 nm. The plot at the bottom of Figure 13 gives an overview of the error behavior over the full positioning cycle. The error is limited to the measurement resolution, with exception for the spikes.

Note that the application domain of the pulse mode is limited to relatively low force applications. Indeed, for a high traction force a large preload is needed. This leads to relatively high fluctuations of the slider trajectory, compromising high-precision applications. Moreover, the maximum drive speed is limited to about 1 mm/s.

Case studies

Linear positioning system with a stepping mode

Extending the stroke of the Leuven motor in the direct-drive mode always requires a retraction of the contact point. In

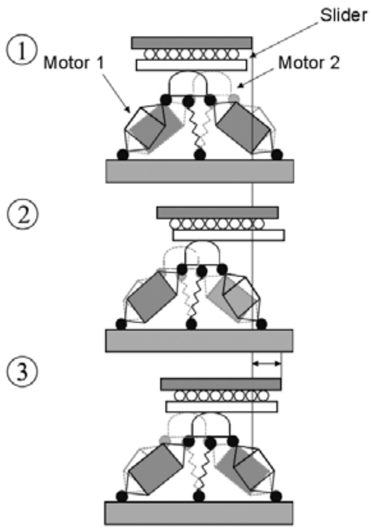


Figure 14. Working principle of the stepping drive. Leuven motor 1 is represented in solid black, Leuven motor 2 in dashed grey.

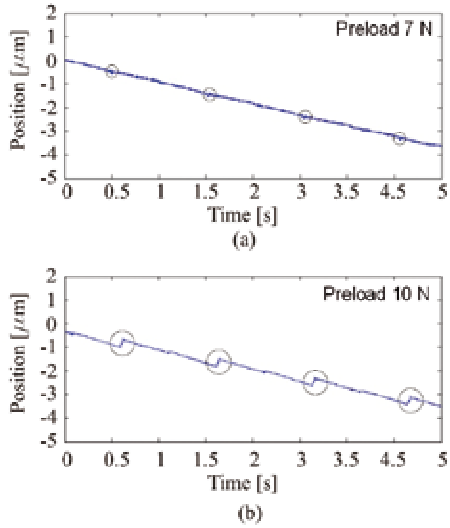


Figure 15. Experimentally measured motion of the slider in the stepping mode.
(a) Preload force = 7 N.
(b) Preload force = 10 N.

the pulse-drive mode, the philosophy is to retract as fast as possible to prevent a distortion on the slider. As discussed above, this retraction causes position spikes. Stepping drives on the other hand are characterized by a form-closed contact strategy. Instead of retracting as fast as possible, the strategy is to retract slow enough to allow corrective actions by the controller. Because slider inertia is not used to prevent retraction of the slider during the retraction period, at least two motors are needed to realize the stepping behavior. One motor is generating the displacement, while the other motor breaks contact with the slider and returns to its original position. Repeating this cycle results in a continuous motion of the stepper. Figure 14 shows the conceptual layout of this drive mode.

Figure 15 shows some first experimentally obtained open-loop results [7]. Figure 15a shows a result for a preload force of 7 N. When the contact switches from one motor to the other, position spikes of 50 nm are observed. For a preload force of 10 N (Figure 15b), these disturbances are already considerably larger. A new suspension design is expected to solve this issue.

Compact and stiff planar positioning system

One of the basic principles in machine design in general and precision engineering in particular is the principle of functional decomposition [8]. According to this principle, each degree of freedom has to be imposed by exactly one machine element. In a classical precision machine, each kinematic constraint is fixed by bearings or imposed by a linear or rotational drive. In order to achieve a multi-DOF positioning system, the bearings and drives often are cascaded. The schematic layout of such a cascaded system is given in Figure 16a. The advantage of this layout is that machine elements can be standardized and the integration of machine elements is facilitated. However, Van Brussel et al. [9] summarized that stacking 1-DOF systems to obtain a multi-DOF system results in a lowered bandwidth and an accumulation of errors. Moreover, stacking leads to a non-symmetric design. In Reynaerts et al. [10], the idea is postulated to combine all motion degrees of freedom into one parallel drive system. This approach is schematically illustrated in Figure 16b. An example of such a system is the Stewart platform. By parallel integration of the various degrees of freedom, the stiffness of the separate actuators adds up.

Figure 17 shows the integration of three Leuven motors into a stiff frame (the rotor), realizing a planar positioning system with parallel kinematics. The Leuven motors both carry

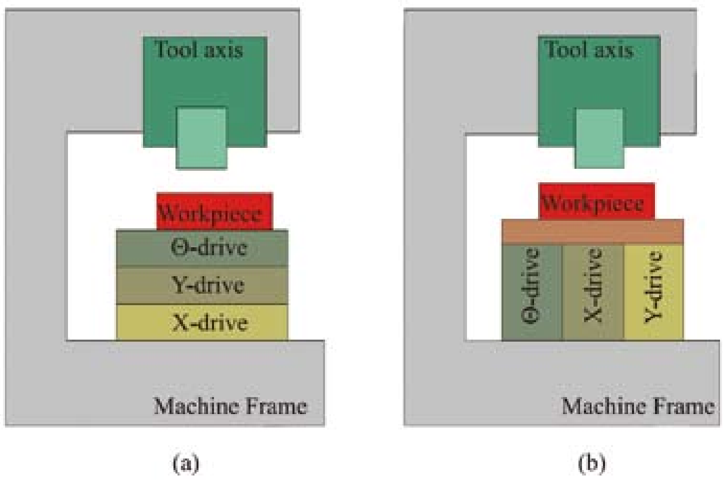


Figure 16. Schematic layout of (a) a classic positioning system, and (b) a parallel system with integrated drive-bearing function.

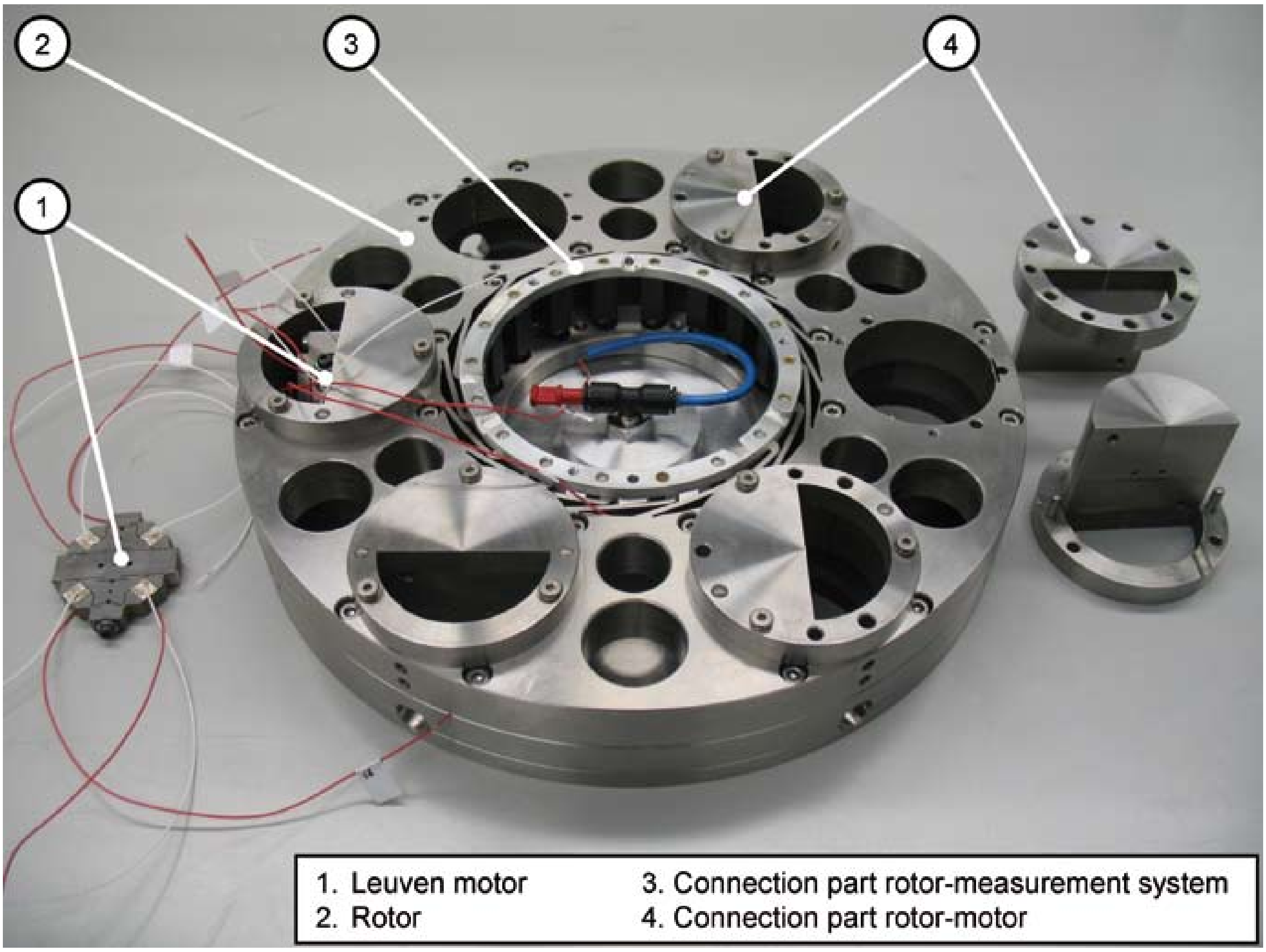


Figure 17. Integration of three Leuven motors into a planar positioning system with parallel kinematics and combined bearing and driving functionality.

and drive the frame, and additionally offer active bearing functionality. A grid encoder is used to measure the position of the frame. Nearly-similar dynamics of the three motors are essential to devise a robust system.

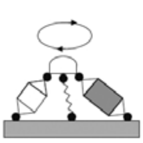
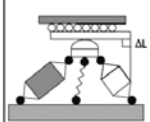
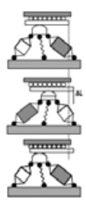
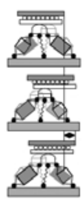
Working principle	Resonant operation mode	Direct drive mode	Pulse drive mode	Stepping mode
				
Stroke	>100mm	5µm	>100mm	>100mm
Speed	300mm/s	50mm/s	1mm/s	1mm/s
Force	12N	>10N	~5N	>10N
Resolution	40nm	10nm	10nm	10nm

Figure 18. Overview of the different operating modes and achieved performance figures of the Leuven motor.

Conclusion

Governed by Moore's Law and pushed by the miniaturization trend, several industrial sectors currently evolve from the micrometre era into the (sub-)nanometre era. In light of this evolution, a novel type of piezoelectric motor has been developed. As elaborated here, this piezoelectric motor – called the Leuven motor – can operate in several drive modes by virtue of an innovative symmetrical design. The direct-drive mode allows imitating the properties of a piezoceramic actuator: high stiffness and (sub-)nanometre resolution within a micrometre stroke. To extend this stroke without compromising positioning resolution, a pulse-mode and a stepping-mode control strategy have been verified. The maximum achievable speed of these modes is about 1 mm/s. Finally, to achieve higher speeds in the order of 100 mm/s, the resonant-drive mode can be used. While being coarser than the direct-drive mode, experiments show that it is still possible to track a reference signal with a maximum error of 40 nm peak-to-peak. Figure 18 summarizes the Leuven motor's characteristics.

As shown in the case studies, the Leuven motor can be used as a core component of a new generation of stiff, compact and non-magnetic positioning systems with a high positioning resolution, wide speed range and a large stroke, capable of operating in demanding environments, e.g. cryogenic and (ultra-high) vacuum. Current research focuses on the tribologic issues related to the friction-drive mechanism [11], and devising control strategies that combine the advantages of the distinctive operating modes.

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Authors' note

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Hendrik Van Brussel is full professor in mechatronics and automation at the Faculty of Engineering, K.U.Leuven. He was a pioneer in robotics research in Europe and an active promoter of the mechatronics idea as a new paradigm in machine design. He is president of euspen (European Society for Precision Engineering and Nanotechnology).
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References

[1] Moore G., Cramming more components onto integrated circuits, Electronics 38/8, 1965.
[2] Taniguchi N., On the basic concept of nanotechnology, Proc. Int. Conf. Prod. Eng., 1974, p. 18.
[3] Van de Vijver W., Development of a highly accurate and fast piezoelectric linear positioning system, Ph.D. thesis, K.U.Leuven, 2008.
[4] Devos S., Development of fast, stiff and high-resolution piezoelectric motors with integrated bearing-driving functionality, Ph.D. thesis, K.U.Leuven, 2006.
[5] Van der Wulp H., Piezo-driven stages for nanopositioning with extreme stability, Delft University Press, 1997.
[6] Chu C.-L., Fan S.-H., A novel long-travel piezoelectric-driven linear nanopositioning stage, Precision Engineering, 30, 2006, pp. 85-95.
[7] Kersschot B. and Leuridan S., Ontwikkeling van een piëzo-elektrische aandrijving met stappende en resonante werkingsmode, M.Sc. thesis, K.U.Leuven, 2008.
[8] Nakazawa H., Principles of Precision Engineering, Oxford University Press, 1994.
[9] Van Brussel H., Reynaerts D., Vanherck P., Versteyhe M., Devos S., A nanometer-precision, ultra-stiff piezostepper stage for ELID grinding, CIRP Annals, 2003.
[10] Reynaerts D., Van Brussel H., Al-Bender F., Devos S., Versteyhe M., Construction and control of an ultra-stiff nanopositioning system, Proc. of 2nd Euspen Int'l Conf., Turin, 2001, pp. 544-547.
[11] Houben M., Van De Vijver W., Al-Bender F., Reynaerts D., A generic study on the contact dynamics and wear behavior of bimodal standing wave piezomotors, Actuator 2008, 11th International Conference on New Actuators, 2008, pp. 176-179.

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