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- THEME: SYSTEMS ENGINEERING & DESIGN METHODOLOGY
- LARGE DYNAMIC RANGE ATOMIC FORCE MICROSCOPE
- BIO-INSPIRED SYSTEM DESIGN
- PREVENTING THE FREEZING OF VACCINES IN A COLD CHAIN

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*The cover image by Henri Werij (featuring the positioning stage of a large dynamic range AFM) is courtesy of TNO. Read the article on page 12 ff.*

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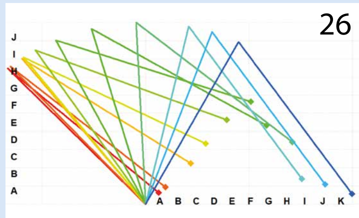
## THEME: SYSTEMS ENGINEERING & DESIGN METHODOLOGY





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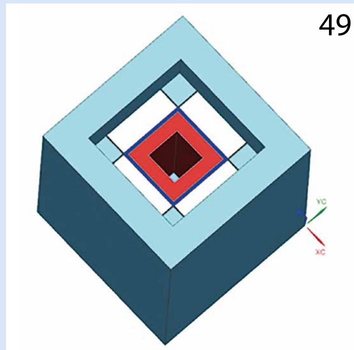

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## FEATURES

# A PRECISION PERSPECTIVE ON SYSTEMS ENGINEERING

Systems Engineering (SE) is hot in the Dutch high-tech community. Some years ago, there was a big boost in the application of SE processes in the civil sector, driven by government demanding the use of SE processes for contractors in infrastructure projects. Recently, we have seen increased focus on SE for the design and engineering of high-tech equipment. Driven by increasing complexity of systems and the accompanying increase in engineering team size, SE is being considered and adopted to better control the engineering processes.

Now, let's take the precision engineering perspective. When looking up a definition of precision engineering on Wikipedia, it highlights the multidisciplinary nature of the discipline to achieve its objective to design accurate, repeatable and stable equipment. One of the fundamental principles in precision engineering is that of determinism. There are many definitions for SE; one description is that of a multidisciplinary field of engineering and engineering management focusing on the development, realisation, etc., of complex systems. So, precision engineering and SE are both multidisciplinary and share a holistic approach, while precision engineering is more narrowly focused on design and manufacturing.

To address the increasing complexity of precision-engineered systems, adopting SE processes more broadly is a natural development. The principle of determinism will drive extensive use of models in the engineering process, for which model-based systems engineering is being developed in the international SE community. This innovation will bring traditional SE much closer to the way of working in the DSPE community, making it easier to adopt SE processes in our work. Precision engineering in the Netherlands will enter a new phase, building on the foundation of design principles as laid down by Wim van der Hoek and his collaborators and successors, and the subsequent extension to the field of precision mechatronics.

At Eindhoven University of Technology (TU/e), the High Tech Systems Center is promoting the use of SE in the research and development of high-tech equipment. This is not an isolated effort: at the University of Twente, SE has been part of the design engineering training for some time, while Delft University of Technology offers SE training with a strong connection to aerospace engineering. Work is required to create innovative interpretations of SE that have a good connection to high-tech equipment engineering and its foundations in design principles and mechatronics. These innovations in SE ideally will be rooted at the Dutch universities of technology and universities of applied sciences. A uniform framework will allow uniform training of new generations of engineers and allow for collaboration in improving and extending it. We don't need a fully independent SE, but we need to adopt a dialect that is sufficiently tailored to our specific world of precision engineering and its application in high-tech equipment.

Artificial intelligence (AI) is a popular topic these days. AI is expected to contribute significantly to the world as we know it. Dutch government has created incentives to promote research and development of AI technologies. The Eindhoven AI Systems Institute has developed a research programme for this field and defined a specific topical area for the intersection of AI and (systems) engineering technologies. One of the research directions is to develop thinking assistants that can support (systems) engineers in the development of systems. The capabilities of AI to manage large amounts of data may prove very useful in the exploration of large design spaces, keeping track of design data and supporting complicated trade-offs. It will be interesting to see how SE and systems engineers will be able to extend their capabilities in managing the complexity of even larger systems.

This edition of your favourite magazine will present these developments from a variety of angles and give you a good overview of where these developments may take us.

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# LINEAR, LOW-MASS, LOW-COST

**A systems engineering approach to the design of a wafer handler is presented, starting with an introduction to wafer handling, followed by the corresponding requirements and lastly common system architectures. Regarding wafer-handling robots, the conclusion is that the moving robot mass increases when contamination requirements become more stringent. Moreover, robotic concepts containing a linear stroke can improve stiffness and reduce mass at the cost of contamination-sealing complexity. To conclude, the design and realisation of a low-end, low-cost magnetic bearing for high-cleanliness robotic applications is discussed.**

RICK BAADE

## Introduction

The front-end-of-line semiconductor manufacturing process contains multiple sequential process steps; one simplified cycle is presented in Figure 1. This cycle is repeated up to 50 times for each wafer. The wafers are transported between manufacturing tools inside a standardised container, called a front-end opening pod (FOUP), which holds 25 wafers. Before each process step, a wafer-handling module is required as an interface between the automated material-handling system (AMHS) that transports the FOUPs and the actual manufacturing equipment. The main task of the wafer-handling module is to extract wafers from a FOUP and place the wafers onto a stage or a chuck, where the actual process takes place. Key functionalities of the wafer-handling module are to transport the wafers throughout the manufacturing tools and, depending on the application, perform position aligning and/or thermal conditioning steps.

Wafer-handling modules usually contain a carrier handler to accept FOUPs, one or two robots for wafer transfer, an alignment module, and wafer storage and conditioning tables. These modules can be designed and supplied by different suppliers, therefore clear requirements on performance and interfaces are important to assure that the fully assembled system, where all modules are combined, meets the system level requirements.

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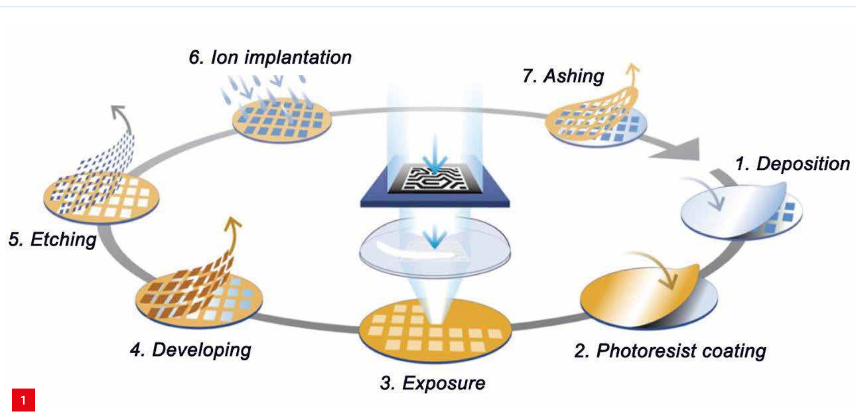


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*Front-end-of-line process cycle (ASML).*

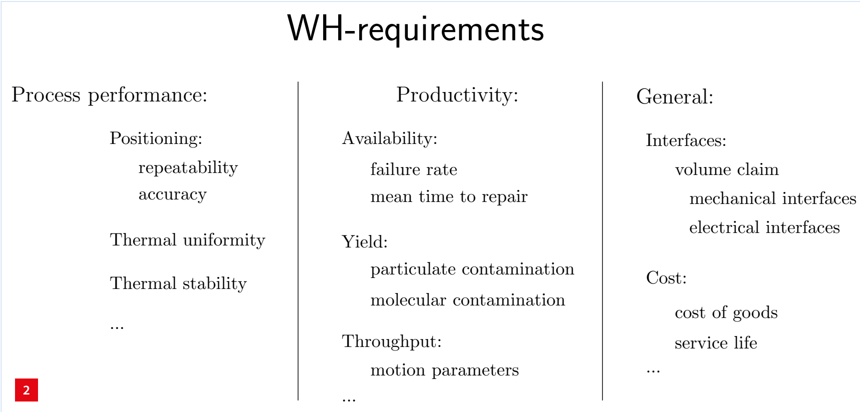
## Requirements

Requirements on wafer-handling modules vary for different applications. A distinction can be made between requirements that influence the performance of the actual manufacturing process and requirements that impact productivity or yield; see Figure 2. Examples of requirements that impact the manufacturing process are position accuracy, thermal uniformity and thermal stability of the wafer. The importance of these requirements and how stringently they are specified depends on the application.

Lithography and metrology steps pose stringent requirements for wafer positioning and alignment, typically in the order of a few micrometers. For chemical and physical processes such as etching or layer deposition tools, wafer-positioning specs are less relevant and in the order of 100-500 micrometers.

Similar to the positioning accuracy specs, requirements on thermal stability and thermal uniformity are challenging for lithography and metrology tools where milli-Kelvin stability and uniformity are demanded. Wafer temperature is less relevant for other process steps; some take place at elevated temperatures of a few hundred degrees Celsius.

Requirements that impact productivity are always important, independent of the application. The complexity of semiconductor manufacturing equipment keeps increasing, following Moore's law, resulting in a continuous




2 *Overview of typical requirements for wafer-handling modules.*

rise in equipment costs. Productivity has to increase to justify the high equipment cost. Defining productivity as a combination of throughput, availability and yield, throughput is mostly limited by the manufacturing process itself and not by the wafer-handling module, although the wafer handler is a significant productivity contributor in availability and yield. Contamination, both particulate and molecular, is believed to be a major source of yield loss. Therefore, key requirements for wafer-handling modules are defined on availability and contamination control.

## Common system architectures

Three main wafer-handling architectures can be identified as corresponding to the requirements, as depicted in Figure 3. The first architecture is an equipment-front-end-module (EFEM), shown in the left of Figure 3. This type of wafer-handling module is used for most atmospheric wafer-handling applications. The EFEM acts as an interface with fabs (semicon fabrication plants) by accepting multiple FOUPs. Inside the EFEM is a wafer-handling robot provided with an extended vertical ($z$)-stroke to enable it to reach all FOUP positions. The robot is often placed on top of a linear axis so it can reach multiple FOUPs placed side by side. In some cases, a wafer aligner module is included for coarse alignment. Most requirements and interfaces are defined in industry standards (SEMI).

The second architecture, cluster tools, is mostly applied for in-vacuum processes and tools that apply parallel operations on multiple wafers. Examples are etching and layer-deposition tools. A cluster tool consists of a central transfer chamber that features a wafer-handling robot at the centre. The transfer chamber has a controlled environment, typically at vacuum pressure. Wafers are fed to the transfer chamber through a load lock that is often coupled to an EFEM. Multiple separate processing chambers are attached to the transfer chamber.

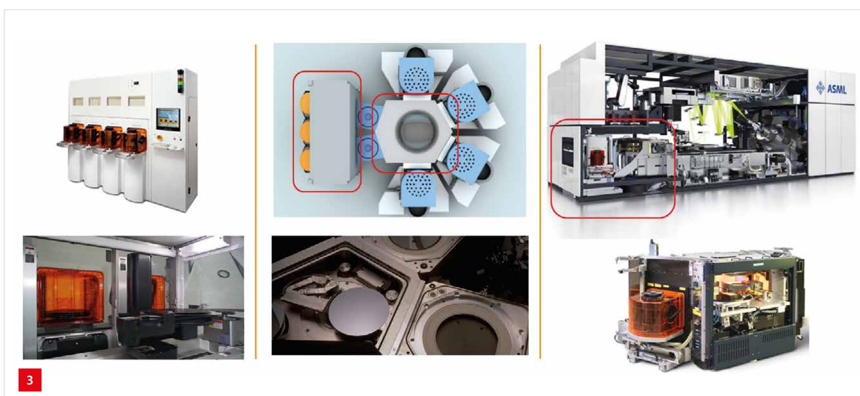
The final architecture is used in applications with the most stringent requirements and often provides additional functionalities, e.g. thermal conditioning. Here, the wafer-conditioning unit is integrated into the manufacturing tool. Integrated conditioning units are seen mostly in manufacturing equipment associated with the lithography step. Multiple tools that are often supplied by multiple OEMs are physically connected. For example, a wafer track that applies photoresist is coupled to the lithography tool. After the lithography step, the wafers return to the track for development. A metrology and inspection tool can also be included in this tool chain. In such a coupled system architecture, wafers are moved between manufacturing tools directly by robots without the involvement of an AMHS and FOUP.

## Wafer-handling robots

Wafer-handling robots are one of the key elements of wafer-handling modules. The robots require three degrees of freedom (DoFs) for most applications, often expressed in spherical coordinates with respect to the robot base. Two in-plane DoFs are indicated by a radial distance $R$ and an angular rotation $\theta$. Additionally, an out-of-plane translation is required along the $z$-axis. The construction of most commercially available robots is based on either a selective compliance articulated robot arm (SCARA) or dual-SCARA kinematic concept, as shown in Figure 4.

The majority of the commercially available substrate-handling robots are relatively heavy compared to their payload, which is a silicon wafer with a mass of 125 g. A typical robotic arm weighs around 4.5 kg. This is due mainly to the limited height that is available to provide out-of-plane stiffness. Moreover, there is a trend towards the moving mass increasing significantly when contamination requirements become more stringent. This is due to the addition of contamination seals that significantly increase the mass, cost and complexity of the system.

The increase in moving mass negatively affects other performance requirements. High-accuracy and high-dynamic motion benefits from a high-stiffness and low-




3 *Three common wafer-handling system architectures, from left to right: Kensington Laboratories (top) and Brooks Automation (bottom); Applied Materials; ASML. See text for further explanation.*

# LARGE DYNAMIC RANGE ATOMIC FORCE MICROSCOPE

**In semiconductor manufacturing, the shrink following Moore's law requires ever tighter overlay and registration between the different (material) layers. For accurately characterising this overlay and registration, TNO has developed a large dynamic range atomic force microscope demonstrator; the LDR-AFM can measure marker-to-feature distances over several millimeters with sub-nanometer reproducibility. It features a highly stable metrology concept and a 6-degrees-of-freedom positioning platform (hexapod) carrying an AFM scan head able to move the AFM probe tip. Repeatability measurements have demonstrated that both drift and reproducibility figures are well below the smallest feature size of the newest semiconductor processing nodes.**

RODOLF HERFST, MAARTEN VAN ES, STEFAN KUIPER, GERT WITVOET, JOOST PETERS AND ROB WILLEKERS

## Introduction

Scanning probe microscopy (SPM) is a form of microscopy that uses a probe to scan a surface in order to form high-resolution images far below the diffraction limit of light in the visible range. Various types and implementations have been developed over the year, but atomic force microscopy (AFM) in particular has revolutionised the imaging industry. It was invented in 1986 [1] and offers high-resolution (down to atomic scale [2]) imaging on relatively cheap and simple instruments.

Two significant drawbacks of the technique however are that it is relatively slow (a few minutes or more for a single high-resolution image), and capable of imaging on only relatively small length scales (typically 100 micron or less [3]). As a consequence, AFM has been mostly restricted to research and laboratory settings and its strengths have not been widely applied in production environments, although there are some examples where it has been used in semiconductor fabs for inspection and process control purposes [4-5].

Naturally, the unique strong points of AFM have led to efforts to mitigate its drawbacks for both general-purpose imaging as well as metrology purposes. Examples are the development of video-rate AFM [6], the high-throughput parallel AFM developed at the Netherlands Organisation for Applied Scientific Research (TNO), now being commercialised by Nearfield Instruments [7], and the large dynamic range AFM (LDR-AFM) [8-10]. This last one aims to drastically increase the length scale accessible by the technique and is the topic of this article. It combines an AFM measurement head optimised for sub-nm accuracy with a highly accurate long-stroke motion stage with six degrees of freedom (6-DoF). This is then mounted in a metrology frame large enough to accommodate 300-mm wafers. We will present an overview of the system's concept and implementation, as well as experimental results that showcase the high performance achieved.

The tool is aimed at providing sub-nm metrology over a distance of several millimeters (i.e., dynamic range > $10^6$). This can be used to characterise both overlay (relative shift) and registration (absolute shift, with respect to a coordinate system) between the different (material) layers in chip fabrication. In established overlay metrology tools, alignment markers are used to assess how large the relative shift between two or more layers is. If the markers are then correctly printed with respect to each other, it is assumed that the device features printed in the same exposure steps as the alignment markers are also placed correctly with respect to each other. However, this is not necessarily the case, especially for the extremely small device features that are possible with the newest lithography techniques, such as EUV. For example, features with a very small pitch can be affected differently by lithography lens aberrations than the coarser marker shapes that are printed for alignment.

To accurately determine overlay of device features associated with, e.g., two different lithography steps, the LDR-AFM is used twice to very accurately measure the distance between a device feature and an overlay marker in each of the two layers. After this, a more traditional (optical) overlay metrology tool determines overlay between the two marker structures. This then gives enough information to infer the overlay between the device features, even if one of those features is not visible anymore in, e.g., a SEM (scanning electron microscope) or AFM image. Apart from aiding in overlay and registration, the LDR-AFM can

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Rodolf Herfst (research scientist), Maarten van Es (scientist), Stefan Kuiper (mechatronics system engineer), Gert Witvoet (dynamics and control specialist), Joost Peters (junior control engineer) and Rob Willekers (research manager, department head) are all associated with the OptoMechatronics department of TNO Technical Sciences in Delft (NL).

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be used to obtain detailed profile information of both device and marker features.
In the next sections, we will first discuss the LDR-AFM's hardware, followed by a brief explanation of how the hexapod positioner is controlled and deals with the inherent cross-couplings. Then, we will go into how the AFM control loop functions. Finally, we will show some results obtained with the system that highlights its potential for metrology applications

## Hardware details

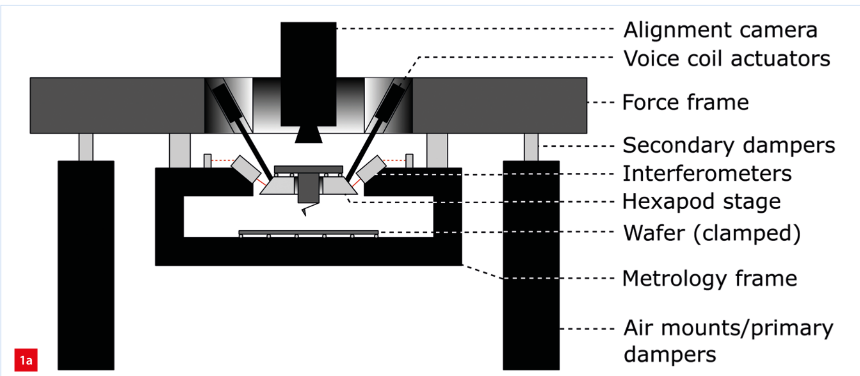
A schematic overview of the system is shown in Figure 1a. At the heart of it, the AFM head with a tilted probe is situated (Figures 1b and 1c). A 6-DoF hexapod positioner [11] can move the AFM head within a hexagon-shaped box (8 mm diameter and 4 mm height). The hexapod is attached to a metrology frame in which a 300-mm wafer can be mounted. The metrology frame is attached to a force frame through (secondary) dampers, which are connected to the ground through the primary dampers.

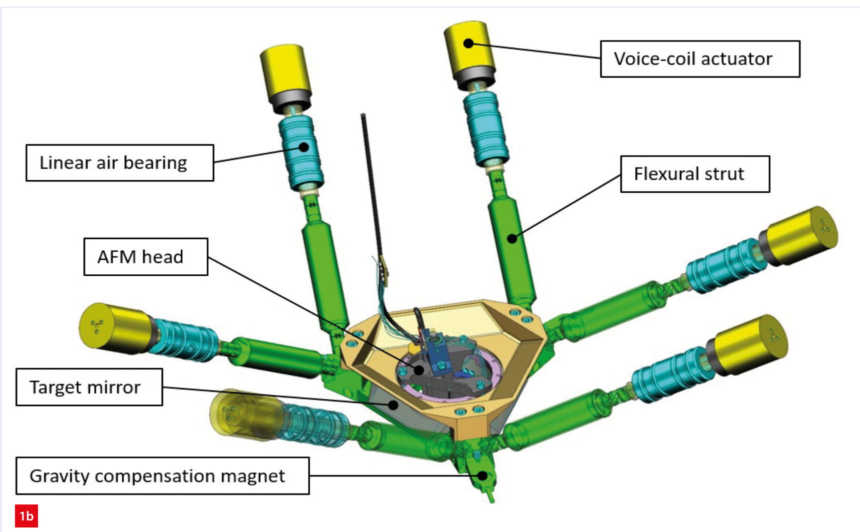
The 6-DoF hexapod positioner uses six voice-coil actuators via flexural hinges to realise translation and rotation. Of course, if no current is flowing through the coils, no (magnetic) forces are generated by them. Therefore, counteracting gravity forces using only voice coils would lead to a large power dissipation, which would in turn heat up the voice coils. In order to reduce this, gravity forces are compensated by magnets on each of the three corners of the stage (see Figure 1b). These magnets are positioned between sets of external magnets, resulting in an upward force on the stage.

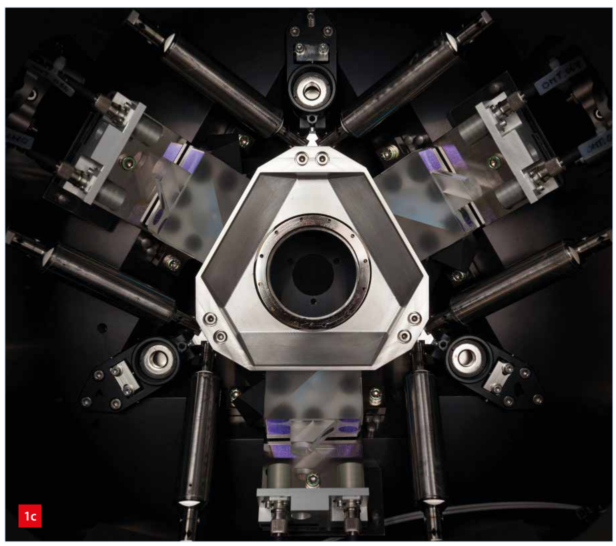
To determine the position and rotation of the hexapod, six laser interferometers are incorporated. The interferometer beams are pointed at target mirrors on each side of the stage. When the hexapod is controlled, the point of which the position should be most accurately known is the tip of the cantilever. In order to reduce Abbe errors at this point, the interferometers are in an orthogonal configuration and the normal of each mirror points toward the AFM probe.

In the AFM head (Figure 2), the AFM chip is attached to the probe holder, underneath which a dither piezo is situated that excites the cantilever. Cantilever motion is measured using the optical beam deflection technique (OBD), featuring a laser diode, a focussing lens, a quadrant cell and associated electronics. The AFM head is held in position in the central hole of the hexapod positioner using dowels and magnetics and can easily be removed for exchanging the cantilever.

Note that the AFM head by design does not have a separate (fast) $z$-stage for the AFM chip, which is common in general-purpose AFMs, but is not required in this specific application, for which a slower, more accurate $z$-stage suffices. Typical piezo actuators used for this purpose (i.e. a separate $z$-stage) are subject to creep and hysteresis,




*The large dynamic range AFM system.*
*(a) Concept.*
*(b) Design (CAD drawing)*
*(c) Realisation with the hexapod 6-DoF positioner and mounted AFM head.*