LIGHTWEIGHT LIFTING

AUTHOR'S NOTE

Max van Lith graduated on the subject of this article at Eindhoven University of Technology (TU/e), the Netherlands. For this work he received a nomination for the 2017 Wim van der Hoek Award. As a Master of Science in mechanical engineering he currently works at Nobleo Technology in Eindhoven.

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A z-mechanism that achieves high cleanliness and highly reproducible motion is proposed for use in the wrist assembly of an in-vacuum wafer handler robot. The required 10 mm stroke is made by an elastic straight guide and contactless actuation. The proposed design has no friction, is backlash-free, and requires no lubrication. A Lorentz duo-motor has been designed for actuation of z and Rx. The application of a buckled leafspring to compensate for weight and stiffness, significantly decreases static actuation forces and heat production.

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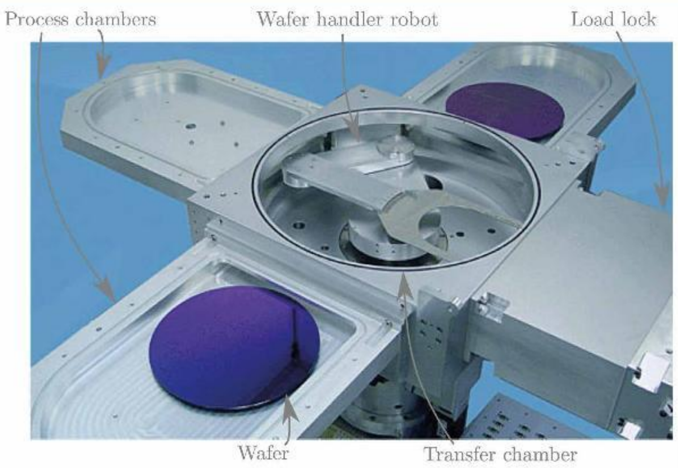
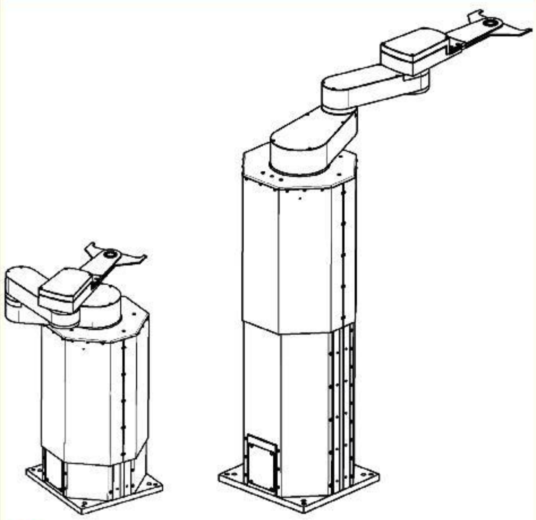
Integrated circuits are manufactured in a layer-by-layer fashion on substrates such as silicon wafers. Multiple production steps require a clean environment and are often performed under vacuum conditions. Examples include layer deposition, etching, and photolithography. Cluster tools can provide the clean vacuum environment where these production steps can be carried out in separate process chambers. An example of a cluster tool is given in Figure 1.

In Figure 1, a wafer handler robot is placed centrally in a transfer chamber. This robot transports wafers throughout the cluster tool. A typical kinematic design of a wafer handler robot has a z-mechanism as a base. The z-mechanism serves two purposes: indexing of a 'foup' (front opening unified pod, i.e., a 'wafer box'), and picking up and putting down wafers. Note that the proposed z-mechanism only takes care of the latter function. On top of the base z-mechanism, a SCARA-type robot takes care of radial and Rz movement, as depicted in Figure 2.



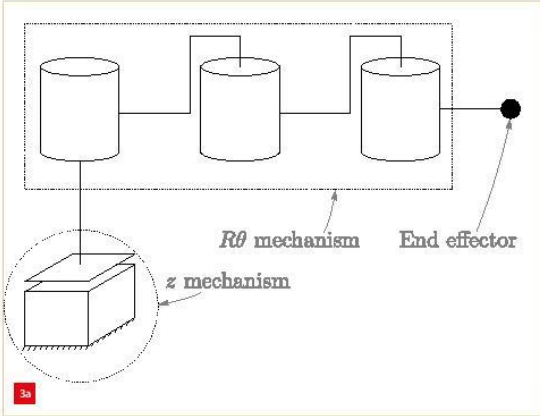
1 *Photo of a typical cluster tool with a wafer handler robot in the central transfer chamber. (Adapted from www.designworldonline.com/advanced-motion-controls-boost-wafer-handling-efficiency, accessed 19-04-2017)*

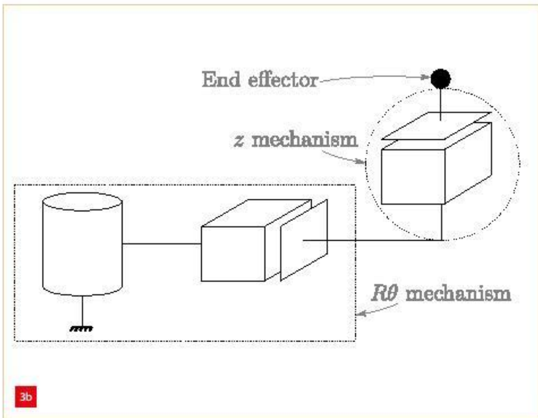


2 *Example of a typical wafer handler robot, shown in two different orientations. The base column provides vertical (z) translation. On top of the base, three serial Rz joints called the shoulder, the elbow and the wrist provide radial and Rz movement. (Source: K. Mathia, Robotics for Electronics Manufacturing, Cambridge University Press, 2010)*

The robotic arm typically has three serial Rz joints, called the shoulder, the elbow and the wrist (Figure 3a). A wafer is transported by moving the SCARA underneath the wafer and subsequently lifting the entire SCARA 10 mm. The z-mechanism therefore has to carry a weight that is significantly larger than the weight of a wafer.

The TU/e Control Systems Technology group is currently collaborating with VDL ETG to improve on the design of wafer handler robots. Key requirements are high cleanliness (both particle and molecular) and minimising the amount of moving mass.





3 *Schematics of the robot arm.*
(a) Conventional design with three serial Rz joints on top of a z-mechanism.
(b) New design with a z-mechanism on top of an Rz (= Rθ) joint.

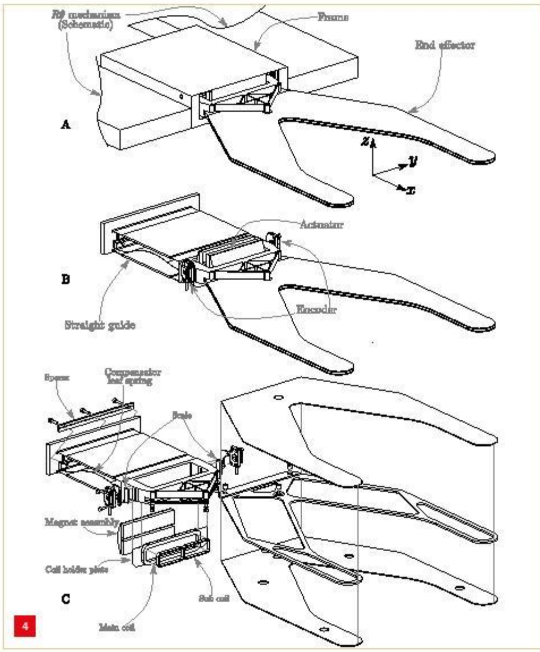
4 *Overview of the proposed design, depicting the main components.*

5 *Cross-section along the X-Z plane of the z-mechanism, depicting the mechanism within the design volume (in red).*

The purpose of this graduation project was to propose a design for a z-mechanism in the wrist assembly of the manipulator. This will decrease the z-mechanism's load from tens of kilogrammes to a few tenths of a kilogramme, allowing for better dynamic behaviour. A volume claim of 150 x 150 x 36 mm^3 (x, y, z) was available for the z-mechanism.

Design overview

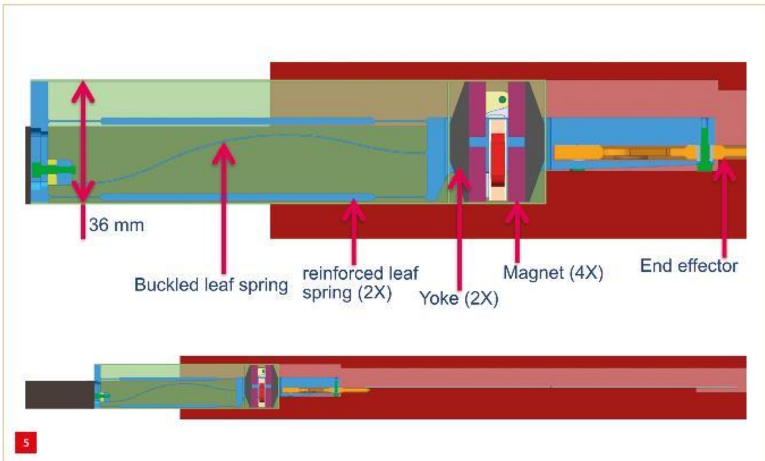
The proposed design (Figure 3b shows a schematic) consists of the following components. A closed box-style frame provides the interface between the wafer handler robot and the z-mechanism. The frame also acts as the 'fixed world' for the magnet assembly of the actuator and the encoders, i.e. the magnet assembly and encoder are attached to the robot side.

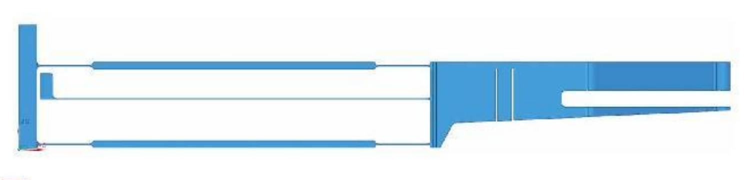


At the heart of the z-mechanism is a flexure-based parallelogram straight guide with stiffness and weight compensation. It is directly driven by a Lorentz duo-motor with moving coils and fixed magnets. Two encoders measure the z-position and the torsion along the x-axis of the straight guide. A two-pronged end-effector is attached to the front of the z-mechanism. This end-effector is made by gluing three pieces of aluminium oxide together. The result is a stiff and lightweight sandwich construction. An overview of the proposed design is displayed in Figure 4. A centre cross-section is presented in Figure 5.

Straight guide: Passively constraining degrees of freedom

A flexure-based parallelogram is used as a straight guide for both the motion of the coils and for the motion of the end-effector. The straight guide is made from a single block of Ti-6Al-4V by wire-EDM. This titanium alloy has a favourable combination of fatigue properties, high elastic modulus and low density. The elastic straight guide exhibits no backlash and no friction. This simplifies controller design and improves motion reproducibility.





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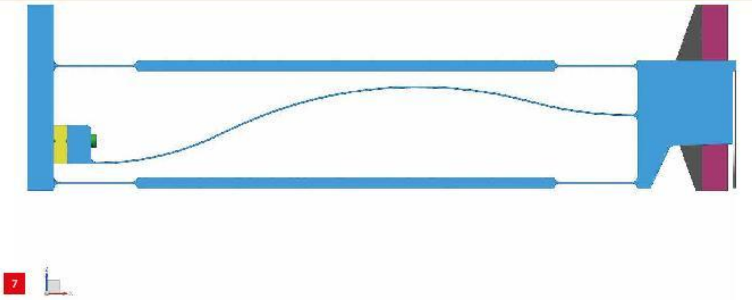
Moreover, flexures do not require lubrication and make no rolling, sliding or colliding contacts. These properties result in high cleanliness. A leafspring, called the compensator, will be cut from the same block of material, such that there is a monolithic connection to the moving part of the straight guide. By buckling this compensator, weight and stiffness in the guidance direction can be compensated for. A side view of the straight guide is given in Figure 6.

Stiffness and weight compensation: Passively reducing control effort

A disadvantage of the flexure-based straight guide is the stiffness in the direction of motion. Moreover, the direct-drive Lorentz motor implies that the weight must be carried by the actuator as well. To minimise thermal issues in the vacuum environment, the actuation forces need to be as low as possible. A linear negative-stiffness spring is used to achieve this. The negative stiffness is chosen close to the parasitic (positive, linear) stiffness of the elastic parallelogram. The negative-stiffness spring is given a preload to function as weight compensation. To achieve the required negative stiffness, and the preload, a leafspring is buckled axially and placed within the parallelogram straight guide. Out-of-plane deflection of the buckled leafspring results in the desired properties.

As previously mentioned, the buckled leafspring can be cut in one set-up from the same material as the parallelogram using wire-EDM. This is presented in Figure 7. Slots in the backplate of the straight guide can be used to adjust the preload of the negative-stiffness spring. This allows for the weight compensation to be tuned, thereby allowing for larger manufacturing tolerances of the flexures. The slots are shown in Figure 8.



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6 *Side view of the parallelogram straight guide and the central compensator spring. The coil holder plates of the actuator fit in the two vertical slots. The end-effector is attached in the horizontal slot.*

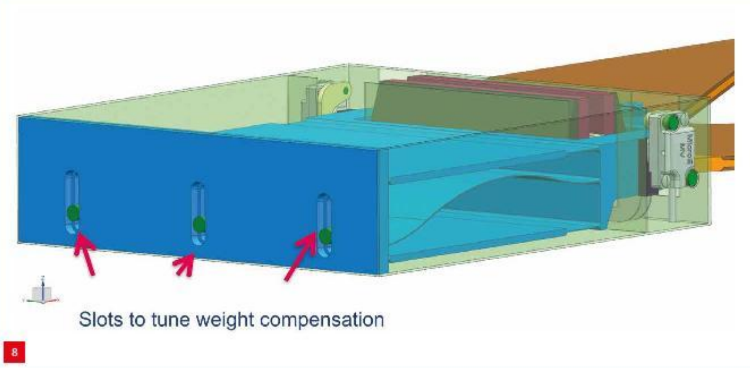
7 *Side view of the flexure-based parallelogram (reinforced leafsprings) with stiffness and weight compensator (buckled leafspring). The result is a straight guide with very low parasitic stiffness.*

8 *Backplate of the compensator, showing the slots that allow for adjustment of the negative-stiffness spring preload. The negative-stiffness spring preload functions as weight compensation.*

Actuation: Actively controlling degrees of freedom

Actuation is achieved with a moving-coil Lorentz motor. This motor features two coils which are glued to ceramic coil holder plates. These plates are in turn glued in slots in the straight guide. The main coil actuates the z-position of the end effector. The sub coil is wound in a figure-of-8 shape, and fits in the main coil. With this figure-of-8 winding, a torque can be produced. This torque may be used to suppress torsional eigenmodes, along the length of the robotic arm (Rx). Figure 9 depicts the working principles of the actuator. By using two encoders, both z-position and Rx can be measured and actively controlled.

Vacuum environments are notorious for causing thermal problems. Therefore, the actuator was optimised towards efficiency. The Lorentz force produced in the coils scales with the product of magnetic flux density, current flowing through the coil and number of wires in a coil cross-section. The first step was to optimise the magnet and yoke thicknesses for maximum flux density through the coil cross-section within a given design volume. The coil was subsequently designed using commercially available, vacuum-compatible wires. For these wires, the maximum allowed current, flowing through a coil, in a vacuum, was retrieved from a catalogue. Together with the wire diameter and a given design volume for the coil cross-section, this made it possible to characterise the actuator specifications.



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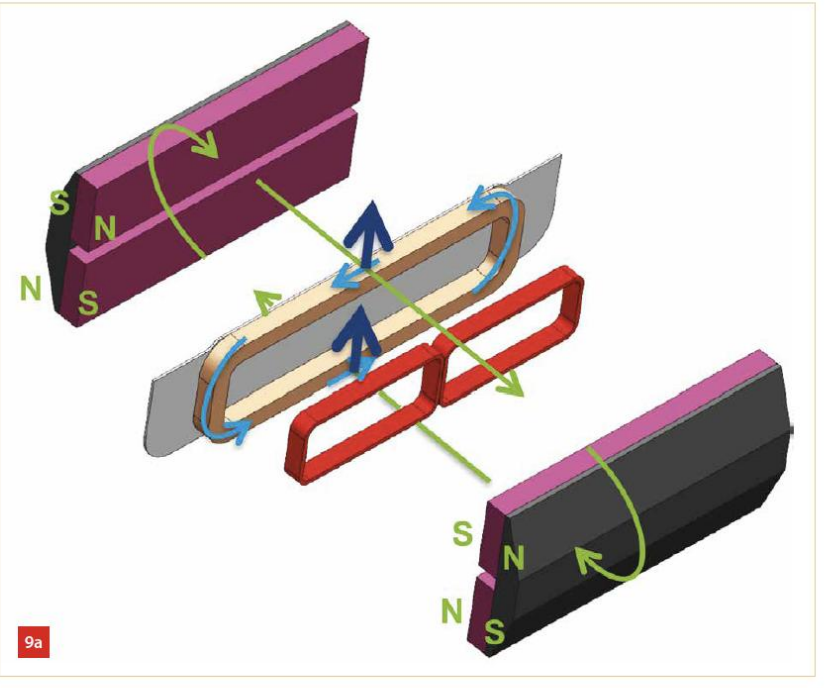
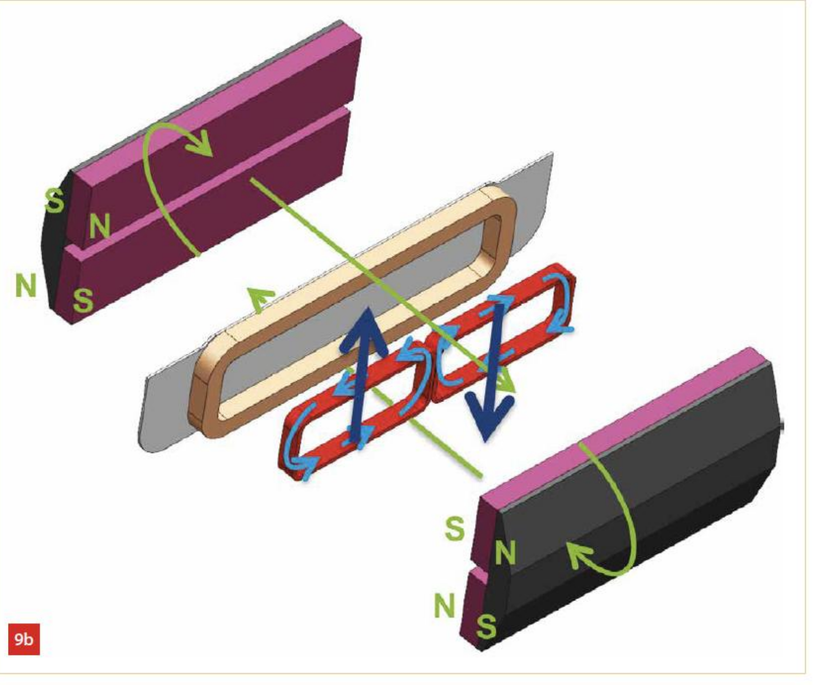
Conclusion

Generally, wafer handler robots have SCARA-like kinematics where the z-translation is driven from the base of the robot. In a collaboration between VDL ETG and TU/e, new technologies for wafer handler robots are being researched. One new concept features a z-mechanism in the wrist assembly of the robot arm for the picking and placing of wafers. The z-mechanism has been designed to achieve high levels of cleanliness. Moreover, high stiffness and low mass allow for good dynamic behaviour and reproducible motion.





9 *Exploded view of the Lorentz actuator. Magnets in purple, yoke in black, main coil in orange, sub coil in red, and coil holder plates in white. Green arrows indicate magnetic flux direction, light blue arrows indicate current flow direction and dark blue arrows indicate resulting Lorentz forces.*
(a) Main coil produces a net force in z-direction.
(b) Sub coil produces a net torque in Rx-direction.

The bending stresses of the straight guide and the buckled leafspring remain well below the fatigue strength to achieve a life span of 10^8 cycles without intermittent maintenance. Within the constraints of this project no prototype was completed for validation. The ambition is to validate the design in a follow-up project. Design topics for further consideration include the planning of the wire-EDM process for this challenging design including negative-stiffness leafsprings and the addition of range limiters to protect the fragile part during transport. ■