Motion Control, Mechatronics Design, and Moore’s Law

Maarten Steinbuch∗ Non-member, Tom Oomen∗ Non-member
Hans Vermeulen∗∗,∗ Non-member

Technology in a broad sense is driven by developments in semiconductor technology, particularly with respect to the computational power of devices and systems, as well as sensor technology. The progress of semiconductor technology has demonstrated an exponential curve since the middle of the previous century, representing Moore’s Law. Consequently, it is of utmost importance to bridge the gaps between disciplines in the fields of control, automation, and robotics. Moreover, data-driven approaches need to be combined with model-based design. This will lead to new digital twinning and automated design approaches that provide major opportunities. Furthermore, this necessitates the redefinition of our university system.

Keywords: Lithography, Motion control, Learning Control, Mechatronics, Moore’s Law, University 4.0

1. Introduction

The Sustainable Development Goals (SDGs) formulated by the United Nations pose researchers and engineers worldwide with new challenges and partly redirect and focus research and innovation. Without hesitation one could say that technology in general and computing power in particular are instrumental for the solutions to be found. IC (Integrated Circuit) technology determines both computational power of devices and systems, as well as sensor technology. Coming decade we will see a tremendous acceleration of smart systems entering almost all aspects of human life and affecting the SDGs: e.g. our health care (1), our mobility (2), our energy systems and climate, our work, our mobile devices. Although we might have the impression that this acceleration is happening only recently, progress of the semiconductor technology can be seen to follow an exponential curve since halfway the previous century. This doubling every fixed time frame has been observed (3) in 1965 for the first time, and is now called Moore’s Law.

In Figure 1, a plot is shown of the computational power on a logarithmic scale vertically as a function of time horizontally, on a linear scale. As can been seen in the figure, the curve even bents upwards from a straight line, on the semi-log plot, meaning that Moore’s Law is describing semiconductor technology even faster than exponentially. The current rate of change is doubling computational power for the same cost, every 1.5 to 2 years. As far as we know it can be expected that this doubling will exists at least for the next ten years, and after that emerging technologies such as quantum computing will be available. We refer interested readers to (3) (4), here we will focus on the consequences for our field, both from a content point of view as well as from an organization point of view.

First, let us look into the technology that in fact drives Moore’s Law. If we look to all processing steps in the manufacturing of IC, thus including front-end (chemical processing, lithography) as well as back-end (die bonding, packaging), it is a direct consequence they all have to follow the same exponential curve. Of these processing steps, the single most impressive and complicated step is the step of writing the actual patterns on a silicon wafer in a lithographic tool. Nowadays, this is done in a wafer scanner machine. This machine, and especially the newest EUV (Extreme Ultra Violet) wafer scanner machine, which costs > 150 ME per piece, can be viewed as the world’s most complicated mechatronic system ever made in mankind: moving masses of around 100 kg, accelerating with over 100 m/s², and next position with a motion accuracy in the order of nanometers in all degrees of freedom in a few milliseconds. As an immediate result, the developments for this machine are the major driver for developing advanced motion control methods (6) (7), as well as mechatronic design principles (8). In Section 2, we will briefly describe the essentials of the machine, and highlight a new feasibility study on superconducting motors and
on an adaptive wafer table. In Section 3 on motion control we will share a comprehensive overview of activities on learning control and the relations with data-based control, AI, system identification, and digital twins for predictive maintenance.

Next to this technical content, in Section 4, before we close with conclusions in Section 5, we will formulate a more philosophical question: if the technology develops exponentially, are we then able to follow and support this sufficiently at our universities, and which paradigm do we need for education and research for the future? In fact, currently, research is being done in a linear way, and this might be too slow. Henceforth, we introduce the notion of the 4th generation of University, or University 4.0, enabling local ecosystems and being much more focused and agile than before.

We might play a crucial role as researchers and engineers, especially in our fields of systems and control, mechatronics and systems thinking, because the world and its SDGs require a much more holistic view.

2. Mechatronic challenges in wafer scanner technology

2.1 A Mechatronics overview of a scanner

Optical lithography is a technology that has enabled mass production of ICs. Nowadays, ICs are used in almost all electrical devices and equipment, including computers, mobile devices and other digital appliances, due to their potential at low production cost. Growth in the semiconductor industry is characterized by Moore’s law: based on a few data points, Gordon Moore predicted in 1965 that the number of transistors in an IC would double approximately every year. This trend, which was adjusted later to a doubling every 18-24 months, has continued for more than half a century, and is expected to continue at least another decade. The law is used by the semiconductor industry to guide long-term planning and to set targets for research and development.

In optical lithography (or photolithography), light transfers a geometric pattern from an image (mask or reticle) to a light-sensitive chemical layer (resist) on a semiconductor substrate (silicon wafer). By far the most common method of exposure is projection printing, where an image is projected through a lens system. Projection is done either stationary (wafer stepper) or by scanning (wafer scanner). In the latter case, the mask (reticle) stage and the substrate (wafer) stage move synchronously in opposite direction while a slit of light is moving at constant speed across the mask. Since multiple dies are exposed sequentially at the wafer, a hybrid step-and-scan approach is typically used. After exposing a field, the wafer is stepped to a new location and the scan is repeated. The wafer scanner allows for reduced dimensions and relaxed requirements in terms of optical aberrations of the projection optics, which results in reduced cost for larger field size. In hybrid step-and-scan systems, however, a full six degrees of freedom isolated machine architecture based on, among others, active magnetic bearing systems was key to enable nanometer-level performance.

After exposure, a series of chemical treatments then either etches the exposure pattern into the material underneath the photo resist, or enables material deposition in the desired pattern upon it. A modern semiconductor wafer may go up to 60 times through this lithographic cycle in order to realize the different layers of a modern device.

Optical lithography is, and will continue to be, vital in semiconductor growth and profits improvement. For reduction in feature size, the wavelength progressed from blue (436 nm) to UV (365 nm) to deep-UV (248 nm and 193 nm) to Extreme Ultra Violet (EUV) (13.5 nm). This wavelength is close to X-ray (below 10 nm) and it is absorbed by all materials including traditional transmissive lens materials and air. Only reflective optics (mirrors) are a practical option for beam shaping in the EUV case. These are covered with a coating with up to 100 layers of Molybdenum and Silicon.

2.2 Towards superconducting motors

Although Moore’s Law is enabled primarily by technology enhancements to cram more components onto integrated circuits, it also predicts the economic advantage of reduced cost per function. In addition to shrinking the dimensions, leading to enhanced functionality per unit of surface area, increased productivity has highly contributed to reduced cost of ownership. Unlike other process steps in IC fabrication, lithography is a die-to-die process, for which velocity and acceleration of the wafer stage and reticle stage are key to productivity. Over the last twenty years, the stage acceleration has been increased by more than a factor five, and for next generation EUV systems, reticle stage accelerations of over 300 m/s² will be used. In combination with a more efficient machine concept based on a dual wafer stage (TWINSCAN TM) and planar motor technology, the productivity in wafers per hour has more than tripled over the last twenty years.

To enable further enhancements in stage acceleration potential, i.e., force per unit of actuator volume, either a further increase in magnetic field density B [T], and/or current density J [A/m²] is required according to Lorentz Law. In currently used linear and planar motors based on neodymium permanent magnets, the magnetic field density at the moving coils is bound to approximately 0.7 T, and the current density in the moving coils is squeezed out to several tens of A/mm² by the application of water cooling. To explore further revolutionary enhancements in stage acceleration, superconducting motors are currently being explored. Thin film rare-earth barium copper oxide (ReBCO) superconductors provide exceptionally high current densities at high magnetic field density in the range of 4 – 50 K. Depending on the applied magnetic field density and orientation, a maximum current density in commercially available superconducting lay-
ers of up to 100 kA/mm² is feasible.

Since the invention in 1911 by the Dutch physicist Heike Kamerlingh Onnes, many superconducting magnet configurations have been developed to reliably operate over long periods of time, e.g., for particle accelerators such as the Large Hadron Collider at CERN and for scanners for magnetic resonance imaging in medical radiology. As opposed to big-science and medical applications, a superconducting coil for a linear or planar motor application in high-tech equipment has specific characteristics and challenges related to the small footprint, high force density, and stable (room) temperature requirements at close proximity to the cryostat. This requires a very high filling ratio with the risk of delamination, a high-stiffness coil support with minimum thermal conductivity (17), and a very thin isolation layer in the magnetic gap of the superconducting motor (18).

A conceptual design (18) (19) of a superconducting magnet plate for planar motor application is shown in Figure 3 and Figure 4. By optimizing the magnetic field density per unit of volume (cost) as figure of merit, an increase in peak magnetic field density by a factor of 6 seems feasible for HTS coils compared to a permanent magnet array. In view of the limited thermal efficiency of cryogenic coolers in the order of a few percent of the Carnot efficiency, the design is optimized for heat load in the coil fixation and thin thermal isolation of the cryostat. A non-contact thermal isolation is proposed based on struts between top and bottom plate and a fully enclosing thermal shield at 80 K, thereby limiting the heat load at 4 K to a few Kelvin, and enabling the use of commercially available cryogenic coolers. Based on a material model describing the layered superconductor with orthotropic material properties, the individual layer stress in the superconducting tape can be calculated. To reduce thermal stress due to cooling down and Lorentz motor forces and avoid tensile stress potentially delaminating the coil, winding pretension is used and additional compressive radial stress is applied to the individual coils.

2.3 Adaptive wafer table To further reduce the minimum feature size or critical dimension (CD) in semiconductor chips, tight control of depth of focus and overlay between successive layers in the lithography process are key. Variations in depth of focus results in CD variation and hence affects performance and yield. One of the main contributors to focus variation is the unevenness of the wafer support, i.e., the wafer table. In view of thousands of wafers being processed per day in high volume manufacturing mode and fast wafer exchange, the flatness of the wafer table is deteriorated by mechanical wear and contamination, negatively affecting overlay and focus performance over a significant area. A first feasibility was conducted on an adaptive wafer table, an active system, which allows for mechanical deformation of the supported wafer in the edge region by means of over 1600 embedded piezoelectric actuators driven via a multiplexer to reduce the number of high-voltage connections (20). Simulations using an electromechanical model, including active hysteresis compensation and a creep operator to limit the effects of the piezo actuator non-linearities, show a performance improvement from over 200 nm to less than 15 nm.

In addition to wafer table unevenness due to wear and contamination, other effects may also result in a mismatch (non-conformity) between the projected aerial image and the image plane. Deviations due to heating effects of the mask, the projection optics and the wafer, and processing effects resulting in intra-die wafer deformations, result in additional in-plane and out-of-plane mismatch between image and image plane. A feasibility study to improve intra-die field curvature via a piezo electrically driven photomask manipulator (21) (22), initiated a study to investigate the potential of an adaptive wafer table, focusing on distributed control and actuation concepts and the mechatronics architecture.

A controller algorithm (23) for an adaptive wafer table to reduce high-frequency thermal induced wafer deformations at high spatial resolution (mm-scale) can be solved using optimization. Based on actuator influence functions, it computes optimal actuator forces that are used in feedforward control. By using the localized feedforward controller around the exposure slit, the thermal induced wafer deformations
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... during exposure are expected to be reduced by a factor 5 to 10. A new concept is described to characterize both in-plane and out-of-plane influence functions with an accuracy of 98 percent, via the employment of both the direct and indirect piezoelectric effect by activating one piezo-element and measuring the charges generated on the neighboring piezo-elements. The charges are then computed into actuator displacements and fitted using solutions to the Biharmonic plate equation with Winkler foundation.

In addition to the intra-die wafer actuation, an adaptive wafer table is currently being investigated, which allows for macroscopic actuation to enable conformal wafer loading. Due to residual stress in the wafer top surface as a result of successive processing steps, such as film deposition, thermal processing and chemical-mechanical planarization, wafer warpage will occur, which, in turn, results in wafer internal stress and deformation. This process is governed by the interaction between the local friction coefficient $\mu$ of the wafer table and the wafer, which may vary due to, e.g., wear, contamination and wafer backside processing, and the normal clamping force, and results in non-reproducible local variations and hence, overlay errors. As the number of layers is expected to continue to grow, especially in 3D-NAND memory applications, where typically 150-300 layers are exposed, wafer warpage is also expected to increase, already up to values of 0.5 mm peak-to-valley. A design for an active deformable wafer table is proposed Figure 5, based on a stack of six piezo ceramic PZT layers with embedded interdigitated electrodes, for controlling both the in-plane strain and curvature degrees of freedom, conformal to the shape of the wafer. Currently, an actuator prototype is being built for experimental validation. See also Figure 6 and Figure 7.

3. Accuracy-Driven Motion Control

Positioning systems are the key enabling technology for machines such as lithographic wafer scanners. In wafer scanners, exposure takes place while the mask stage and substrate stage move synchronously with a constant velocity with nanometer accuracy. A motion control system determines the desired actuator inputs, see Section 2.2, based on the desired reference $r$ and measured actual position $y$.

Traditionally, mechatronic systems are designed such that the relevant performance variables are not significantly affected by mechanical and thermal deformations during normal operation. In particular, the mechanics of a motion system such as a wafer or reticle stage, can be approximated as a linear dynamic system and can be represented by the transfer function matrix:

$$y(s) = \begin{bmatrix} \sum_{i=1}^{n_{RB}} \frac{c_i}{s^2} + \sum_{i=n_{RB}+1}^{n_f} \frac{c_i}{s^2 + 2\zeta_i\omega_i s + \omega_i^2} \end{bmatrix} u(s)$$

where $y$ is the output position, $u$ is the actuator input, $n_{RB}$ is the number of rigid-body modes, the vectors $c_i \in \mathbb{R}^{n_a}$, $b_i \in \mathbb{R}^{n_a}$ are associated with the mode shapes, and $\zeta_i, \omega_i \in \mathbb{R}$. Here, $n_f, n_r \in \mathbb{N}$ may be very large and even infinite. Variable $s$ is a complex indeterminate due to the Laplace transform. In traditional motion systems, the flexible modes are often far beyond the target bandwidth and considered as parasitic dynamics. Note that in this paper we do not consider the broader and different class of (non-linear) robotic manipulators.
3.1 Traditional motion control

A typical motion control architecture for wafer scanners is depicted in Figure 8, where the goal is to let the output of the system $y$, typically a position, track the desired reference $r$, hence to minimize the error signal $e = r - y$. To this end, two design choices are made by the control engineer: the feedforward control signal $f$ and feedback controller $K$ in Figure 8.

In most industrial motion system designs, where the flexible modes in (1) are significantly beyond the bandwidth frequency, high control performance can be obtained by designing the feedback controller $K$ by Proportional-Integral-Derivative (PID) filters for each rigid-body motion degree of freedom, possibly with additional notch filters (29) in case the (reproducible) parasitic flexible dynamics endanger closed-loop performance or stability. These filters are easy to tune using measured frequency response functions (28) (30). The basic idea is depicted in Figure 9, where each motion degree of freedom has one actuator/sensor pair associated with it, leading to a decentralized control structure.

The feedforward controller for predominantly rigid-body systems also directly follows from (1). Indeed, the rigid-body dynamics satisfy Newton’s second law, hence through acceleration feedforward $f = \dot{m}\ddot{r}$, where $\dot{m}$ is an estimate of the mass and $\ddot{r}$ is the reference acceleration profile for each motion degree of freedom. Additionally, velocity and friction feedforward schemes can be added if appropriate.

Despite excellent mechatronic designs, increasing performance and throughput requirements have spurred refinements in feedforward and feedback control design (31) (32) (33). For example, the feedforward has been extended with snap feedforward (34) to compensate for the compliance associated with the flexible modes in (1).

In addition to these improvements in controller tuning, we envisage a radically new design of future mechatronic systems, which will become data-intensive due to the use of many sensors and actuators, in addition to new mechatronic designs (35). These will lead to improved performance and system availability of future machines, leading to high accuracy, throughput, and reduced cost.

3.2 Over-actuated and over-sensed motion control

Traditional motion performance is limited by the flexible dynamics in (1). In particular, the closed-loop bandwidth generally has to be substantially below the frequency at which flexible modes occur, see (36, Section 3) for a detailed analysis. In addition to viscoelastic and viscous passive damping solutions (37) (38), overactuation and oversensing significantly open up the solution space to further enhancements. A key idea in overactuation and oversensing is to avoid excitation of internal resonances in the rigid body transfer function, to improve the rigid body estimate at the point of control, or to actively suppress (dampen) vibration modes and shift limiting flexible dynamics to higher frequencies (39) (40). In particular, this directly enables higher accuracy through increasing the control bandwidth. Also, it enables radically new system designs that are lightweight and can therefore achieve much higher accelerations, since the maximum acceleration is reciprocal to the mass of the stage (41, Section 1). Interestingly, new motor concepts, including planar motors, see Section 2.2, directly enable the application of spatially distributed forces to actively control mode shapes. The words overactuation and oversensing stem from the fact that more actuators and sensors are being used as there as rigid-body degrees of freedom. This area is already an active research area for decades in the field of flexible solar orbital systems, aerospace and adaptive optics. Over the last 5-10 years, it has been entering industrial motion systems, in particular for wafer stage systems.

Regarding feedback control, the idea of overactuation has led to a major increase in stiffness and damping of...
performance-limiting flexible modes. Consequently, this has enabled improved closed-loop bandwidth and improved position accuracy. The key idea in this approach is to identify models of the flexible modes, see (42) for recent developments. Next, this model is used in a robust control design based on \( \mathcal{H}_\infty \)-optimization (43), where this model is internally used as an observer (45). In turn, this allows to actively compensate the mode-shapes, see Figure 10.

Regarding feedforward control, the use of spatially distributed actuators allows beating major performance limitations. Indeed, while non-minimum phase zeros directly introduce additional fundamental performance limitations for feedback systems (46), their practical implications are often limited. In sharp contrast, for advanced feedforward design non-minimum phase dynamics lead to difficulties (47) (48). Interestingly, non-square systems, where the number of actuators is larger than the number of performance variables (49), generally do not have non-minimum phase zeros, enabling perfect causal feedforward, see (47) for a recent advanced motion feedforward approach.

Overall, these developments in both feedback and feedforward control reveal that increased controller performance is directly achievable for positioning systems. In turn, it also allows for new system designs, since flexible dynamics in (1) can be made stiff and well-damped by active control, instead of mechanical design. This paves the way for revolutionary lightweight system designs that allow much higher accelerations and throughput.

3.3 Multiphysics models for thermo-mechanical motion control

In view of increasing accuracy and throughput requirements, the model (1) must be extended to include thermal aspects to achieve (sub)nanometer accuracy. Indeed, increased accelerations require additional actuator power, see Section 2.2, leading to thermal gradients and consequently thermo-mechanical deformations. In addition, increasing performance requirements imply that these thermo-mechanical deformations become increasingly important in the overall error budgets (49).

The key idea (49) is to address thermo-mechanical aspects in precision motion control, as occurring in wafer stages, by introducing thermal control loops and interconnecting these with motion control loops, see Figure 11. These approaches include new estimation techniques, where the thermo-mechanical deformations are estimated using temperature measurements and accurate multiphysics models of the system, which are consequently used to compensate in the (high bandwidth) motion control loops. Also, the temperature measurements are used directly in thermal control loops, including the use of Peltier elements for accurate temperature control.

A major challenge in these thermal control loops are the slow time constants and potentially large external disturbances that hamper the modeling process. To this end, major improvements have been made regarding non-parametric frequency response function identification in the last decade (50). These approaches have been further developed and tailored towards thermal systems, where in addition external temperature sensors enable a substantial further improvement of the identified models, see Figure 12 (51).

3.4 Centralized control for synchronizing subsystems

The idea of combined thermal and mechanical control can be pushed even further, by realizing that contemporary wafer scanners consists of a large number of subsystems that jointly cooperate to produce more accurate ICs with increasingly high throughput. As a prime example, these wafer scanners now move synchronously the mask (reticle) stage and substrate stage in opposite direction, during which exposure takes place. These stages are traditionally given their own setpoint, and do this independent from each other. In sharp contrast to the mask stage, which performs its motion repetitively with the same reference, the substrate stage moves stepwise over the entire wafer surface, leading to a much heavier stage with position-dependent dynamics (52).

A key observation (53) is that the absolute errors of the individual stages are irrelevant: only their relative error is a...
key performance indicator for the quality of the resulting ICs. Therefore, a new double-Youla\cite{52} framework is presented\cite{52}, which aims to connect the decentralized feedback loops in a unified way, enabling bidirectionally coupled control loops, see the integrated controller of the two subsystem control loops in Figure 11. As is shown\cite{52}, this allows the faster and more high bandwidth reticle stage to compensate for errors that occur in the substrate (wafer) stage, leading to a substantially smaller relative error, which in the end is the key performance indicator.

3.5 Opportunities for future data-intensive mechatronic system designs: learning and digital twins  The preceding Section 3.2, Section 3.3, and Section 3.4 reveal that future systems will exhibit much more complex dynamics over large dynamic ranges that need to be compensated with a large number of spatial actuators in different physical domains. At the same time, the number of sensors grows drastically, and huge amounts of data are available, as well as a large computational power for real-time processing in control algorithms\cite{54}. This leads to two major opportunities in future data-intensive mechatronic system designs, outlined next.

3.5.1 Learning for achieving the limits of performance  The abundance of data in future mechatronic systems provides a huge potential for major performance improvement through learning. In sharp contrast to many recent achievements in machine learning and artificial intelligence, learning in industrial machines requires algorithms that are fast and safe\cite{55}. Fast convergence is required, since experiments have to be done in real-time, and model-free algorithms require huge amounts of data, see also the recent overview\cite{56}. Furthermore, robustness is a key aspect to ensure human and machine safe operation. These observations have led to a framework for learning in advanced motion control, see\cite{52} for a recent overview, where many recent developments in machine learning, including Gaussian processes\cite{57}, as well as stochastic and sparse optimization.

3.5.2 Digital Twins for Fault Detection and Predictive Maintenance  The availability of an abundance of data in conjunction with improved models that are used for control design, see Section 3.2 – Section 3.4, provides a major opportunity to monitor performance and increase system availability. In turn, this allows a major increase in throughput of industrial motion systems in general and wafer scanners in particular. Indeed, in traditional model-based control applications\cite{58}, the model is only used to design a feedback controller, and after the controller is implemented, the identified model is being disposed of. The main idea in\cite{59} and\cite{60} is to use the identified model in real-time, to detect and isolate faults, as illustrated in Figure 13. This automatic diagnostics provides major opportunities for system reconfiguration, e.g., temporarily redistribute the forces in the overactuated motion control setting in Section 3.2 in case of a damaged actuator, as well as move towards predictive maintenance to maximize system availability.

4. The Fourth Generation University  As stated in the introduction, the technological developments are rapidly progressing and have impact in all aspects of our lives, such as energy, mobility, health, security, working, living. We also might call this the digital society, with internet of everything as driving principle. The speed of change is accelerating, and is driven by the exponential growth of computing power dictated by the Moore’s Law.

The question to be discussed in this section is the following: how are we going to speed up the research at our universities? How do we stay connected and how can we follow the accelerations of innovations?

The answer might be to define a next generation of university: a networked university, with open channels to industrial, entrepreneurial, societal engaged individuals. Where innovation is not done in isolation, but in co-operation, with customer participation. An open innovation space. We call this the 4th generation University, or University 4.0 for short. Related ideas are also discussed by\cite{62,63} and\cite{64}. Some novel ideas also appear in the work of\cite{65}, denoted as interversity.

4.1 A short history of university development  Let us first describe the first generations of universities to put the envisioned direction into perspective\cite{66}.

The first generation of university was focused only on education, and goes back maybe thousands of years ago into the ancient cultures of China and India. The first form of this kind in Europa is the University of Bologna (1088). Then the second generation introduced scientific research as the additional key goal. The example of this type is the Humboldt University Berlin.

The (current) third generation of university was initiated by Cambridge University. The third added element was that of valorisation. This in fact means the role of initiating market innovations, helping start ups and bridging the gap with industrial applications by bringing the ideas outside the university.

The table\cite{66} in Figure 14 nicely shows the typical ingredients of the three types of universities. All three categories have different characteristics with respect to management, languages spoken, and focus.

If we observe how our current system works, the third generation of university is still not everywhere implemented, but we see a strong drive, also in the Netherlands, to work more inter-disciplinary, focus also on entrepreneurs and think about how to create value. The technical universities and those in the life sciences typically lead the way in connecting to industry and having impact via businesses.

Nevertheless, our research processes themselves are still very linear: we do research, starting with a thorough survey of literature, then investigate, then write a paper, submit it, get after 3 months or so reviewer feedback, modify, send again, and after one or two iterations we hope to have it published say one year later. We repeat this several times, and after a few years our Hirsch index is increased by one, and as a young professional you might get promoted to the next academic level after several of those iterations.

4.2 Towards University 4.0  As stated at the start of this article, the world around us is changing fast, and linear thinking and linear processes are replaced by exponential growth, using the power of platforms (i.e., networks), and circular processes. So we can observe a divergence between the pace of university research and its environment, although we know of course that doing research with high quality requires time and dedication. Although we should respect these latter
values, we would like to propose the 4th Generation of University, with, on top of the regular primary educational and research tasks, the following key ingredients:

- the university becomes a dynamic open innovation space;
- part-time positions for industrial ‘residents’, artists, and employees of governmental, societal or other knowledge institutions;
- part-time employment for scientists in positions outside the university;
- BSc and MSc student teams and PhD participation in benchmark or worldwide games for societal challenges;
- inter-disciplinary teams with pressure cooker sessions, like hackatons;
- the focus of the university is partly global, but it has a strong local network and is the (co)driver of its local ecosystem;
- the role is not just creating value (3rd generation, see the table in Figure 14) but merely to enable to let the (local) network create value, so the university is an enabler and motivator.

Some of the ingredients are already implemented in practice to a certain extend, and the list can be longer. Some very strong examples in the Netherlands have been the ‘knowledge workers’ arrangement back in 2008-2010 during the worldwide financial crisis. Back then, employees of the industry were relocated at the Dutch universities to deepen their knowledge and to give inspiration to the scientists. As an example, we developed in our group hybrid power trains for commercial vehicles with the local industry. Also, at many places, people from industry now have part-time positions. Nevertheless, in order to speed up research and impactful innovations and use the capabilities of universities, this can amplified as a new way of working. The challenge is to maintain our quality standards (partly realized via the earlier mentioned (slow) peer review process) and scientific reproducibility of the results as the main key scientific values.

The table in Figure 15 summarizes the ingredients of the newly proposed 4th generation university, in a comparison with the 3rd generation.

Interestingly, in our region, also called the Brainport region, we are very close to such a networked environment for innovation, and our Eindhoven University of Technology could play a role as a trendsetter for this 4th generation university. We are already very active with the implementation of challenge-based education. Now we need a step towards challenge-based research in co-operation with our (local) en-
vironment.

### 4.3 How to start

It is questionable if the trend toward the next generation of university can be realized fast enough from within. One limiting factor is that knowledge generation and dissemination are normally followed by industrialization via existing companies or by founding startups. If we really want to speed up, the least we should do is practice concurrent innovation.

Like the ‘disrupt your mother’ spin-offs of large companies, it can be argued that a separate entity might enable this change faster. For that reason we founded Eindhoven Engine with the assignment and mission: How can researchers, investigators, founders, innovators and entrepreneurs best use our collective intelligence to focus on future challenges? How can we create innovative processes and explore all the possibilities? The question becomes, “Are we fast enough? Can we scale fast enough?”

An even bolder move would be research and innovation through trial and error, through iteration loops and through learning by doing. And, of course, we need to devote more resources to innovation, including capital and talent. In fact, if we co-innovate by bringing together people from academia and from industry, we will accelerate all innovation processes, balancing between creative disruption divergence and focus.

It is crucial to motivate researchers and executives to unite in our efforts to accelerate innovation. In the research space, our knowledge partners, Eindhoven University of Technology, TNO (Netherlands Organisation for Applied Scientific Research) and the Fontys University of Applied Sciences, make sure we have the resources to understand, then solve, real-world problems. At the same time, this collaboration allows us the freedom to look far into the future, anticipate what is coming next, then leverage these insights. This stimulates researchers to invent new solutions in the form of new theories and new conceptual designs and architectures. Combining new ideas with young entrepreneurs as well as experienced people into startups or new business for existing companies leads naturally to new implementations in society.

Cross-domain information exchange is crucial to co-creation. We call this “enabling” or “unleashing” our collective intelligence. It is obvious to implement in established ecosystems such as Brainport. And digital networking will also help build and sustain a global network of innovators dedicated to exponential innovation.

We are living in a very interesting time, in which new technologies emerge quickly, and societal challenges are compelling. We see the potential, and we should do our utmost best to increase the speed of innovation. Connecting people and using our networks are the key ingredients for success. In the end, it is all about people and unleashing their full potential, in order to solve the Sustainable Development Goals.

### 5. Conclusions and Recommendations

In this paper, Moore’s Law has been used as a inspiration to investigate the implications of exponential growth of computing and sensing power for motion control, mechatronics as well as the future of our university system. Key findings are the need for in-depth cross-disciplinary research within mechatronics, i.e., where precision mechanics meets advanced modeling and (data based) control in the combined motion and thermal domain, along with new paradigms e.g. for actuator design such as superconducting motors, and for adaptive wafer tables. For universities we described characteristics of the 4th generation university as an enabler for local ecosystems. It is emphasized that many other aspects are relevant in view of the Sustainable Development Goals. For example, here we did not widen our engineering scope to ethics and social sciences in view of the Sustainable Development Goals. It is clear that new technology is a necessity but not a sufficiency for our society.

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Maarten Steinbuch (Non-member) He received the M.Sc. (cum laude) and Ph.D. Degree from Delft University of Technology, in 1984 and 1989 resp. From 1987-1999 he was with Philips Electronics. Since 1999 he is full professor Systems and Control and chair of the Control Systems Technology group of the Mechanical Engineering Department of Eindhoven University of Technology. He was Editor-in-Chief of IFAC Mechatronics (2009-2015), and is chairman of the supervisory board of SIOUX Group BV, and has various other advisory roles. He is (co)founder of MI-Partners, Mechatronics Academy, Preceyes, MicroSure, ZEnMO, Eindhoven Medical Robotics. Since 2018 he is Scientific Director of Eindhoven Engine. In 2003, 2005, 2008 and 2015 he obtained the 'Best-Teacher' award of the Dept. of Mechanical Engineering, TU/e. In 2008 as well as in 2014 his research group obtained the QANU excellence rating [5555]. In 2013 he was appointed Distinguished University Professor at TU/e. In 2015 he received the KIVI Academic Society Award. In 2016 he was awarded as Simon Stevin Meester 2016, the highest Dutch award for Scientific Technological research. His research interests are modeling, design and control of motion systems, robotics, automotive powertrains and systems and of fusion plasmas. He is IEEE Fellow.

Tom Oomen (Non-member) He received the M.Sc. degree (cum laude) and Ph.D. degree from the Eindhoven University of Technology, Eindhoven, The Netherlands. He is currently a professor with the Department of Mechanical Engineering at the Eindhoven University of Technology. He is also a part-time full professor with the Delft University of Technology. He held visiting positions at KTH, Stockholm, Sweden, and at The University of Newcastle, Australia. He is a recipient of the Corus Young Talent Graduation Award, the IFAC 2019 TC 4.2 Mechatronics Young Research Award, the 2015 IEEE Transactions on Control Systems Technology Outstanding Paper Award, the 2017 IFAC Mechatronics Best Paper Award, the 2019 IEEE Journal of Industry Applications Best Paper Award, and recipient of a Veni and Vidi personal grant. He is Associate Editor of the IEEE Control Systems Letters (L-CSS), IFAC Mechatronics, and IEEE Transactions on Control Systems Technology. He is a member of the Eindhoven Young Academy of Engineering. His research interests are in the field of data-driven modeling, learning, and control, with applications in precision mechatronics.

Hans Vermeulen (Non-member) He received a M.Sc. degree, M.T.D. Post-Master’s degree and Ph.D. degree at the Eindhoven University of Technology. From 1999 till 2007 he was with Philips Electronics, of which two years in Pittsburgh, PA, where he worked on EUV and Nano-Imprint lithography systems. In 2007, he joined ASML, where he was senior research manager from 2012-2017, and currently, senior principal architect for the EUV high-NA optics system closely collaborating with Carl Zeiss - SMT. In 2010, he received the ASML Patent Award 2010 for most invention disclosures and patent applications company wide. He is (co)author of over 70 patent applications. He was chairman of the national R&D Work Group Mechatronics at the High Tech Systems Center at TU/e from 2011-2017. From 2015 on, he is part-time full professor at the Eindhoven University of Technology in the Control Systems Technology group with a chair in Mechatronic Systems Design. He is member of euspen, ASPE and CIRP, and technical trainer at the High Tech Institute - Mechatronics Academy in Design Principle for Precision Engineering, Mechatronics, Dynamics and Modeling, and Passive Damping for High-Tech Systems. His research interests are in the field of superconducting linear and planar motors, extremely accurate and fast electromagnetic and piezoelectric (EUV) motion systems, adaptive optics, and medical robotics for vascular and interventional X-ray imaging.