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- THEME: THE FUTURE OF PRECISION ENGINEERING
- MACHINE LEARNING FOR INDUSTRIAL MOTION CONTROL
- FUTURE-PROOF DESIGN PRINCIPLES
- NONLINEAR CONTROL TAKES OVER?
- PRECISION FAIR 2024 PREVIEW

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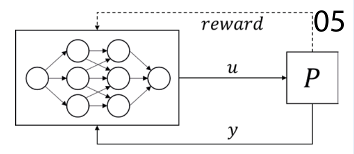

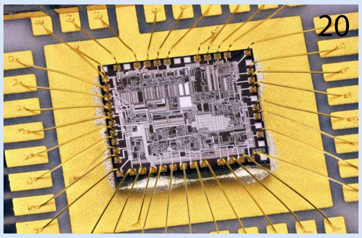

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LIFE-LONG LEARNING: DSPE PROMOTES MICROCREDENTIALS

The certification programme of DSPE – begun in 2008 and taken to the European level through a collaboration with euspen in 2015 – has been successful, with many professionals following post-academic precision engineering courses to their satisfaction. However, providing participants with their certificates still is a labour-intensive procedure. DSPE therefore decided to look for a digital solution.

In 2012, Harvard University and MIT founded edX, one of the first platforms to offer microcredentials through their ‘MicroMasters’ and ‘Professional Certificate’ programmes. Microcredentials serve as a digital diploma for a short (micro-)educational entity, such as a course, mainly for life-long learning journeys. As of now, DSPE will also use these microcredentials in their certification programme. Characteristics of a microcredential include clear learning outcomes, alignment of the course material with these learning outcomes, study load in hours, educational level (NLQF), and individual assessment of trainees on learning outcomes.

NLQF, the Dutch National Qualifications Framework, is a system used to categorise and benchmark qualifications, typically focusing on educational standards and labour-market needs. The post-academic precision engineering courses are on a master level, which is NLQF 7 (academic), but DSPE aims to extend its offer to levels 6 (university of applied sciences (UAS), bachelor), 5 (associate degree, first two UAS years) and 4 (advanced vocational level). Extending the scope to cover NLQF levels 7 to 4 will result in the inclusion of courses covering essential capabilities in the precision domain, such as instrument making, in the life-long learning programme.

DSPE will use the services of Diplomasafe, the Denmark-based developer of credentialling solutions, to ensure the availability of microcredentials anytime, anywhere.

It is DSPE’s ambition to include many (existing and new) courses in the domain of precision technology. Subsequently, DSPE will define learning pathways for professionals that will create possibilities for life-long learning for precision engineering specialists.

DSPE, as a society with many top specialists in its ranks from all the necessary disciplines in the high-tech industry, is the best-suited party to judge the societal relevance and quality of precision engineering courses and life-long learning pathways. For this reason, DSPE is forming an Educational Board. Just Herder, professor of Interactive Mechanisms and Mechatronics at Delft University of Technology (NL), has agreed to chair the DSPE Educational Board. The board will involve the best specialists in the industry to judge courses for the microcredential programme.

With the introduction of microcredentials, DSPE aims to provide a recognised quality mark to benefit both participants in their careers and course providers in their visibility, and to help industry to advance its human resource expertise, thereby benefiting the whole ecosystem. All of these stakeholders are invited to join this effort.

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MACHINE LEARNING FOR INDUSTRIAL MOTION CONTROL

The recent explosive progress in machine-learning (ML) applications raises the question what ML has to offer for industrial motion-control systems. We aim to explore how the power of ML can be safely harnessed for real physical machines, and provide insight into design aspects that contribute to success. Successful ML-based applications at Sioux Technologies are presented, providing a hands-on perspective on the performance potential in motion-control applications.

LENNART BLANKEN AND CASPAR GRUIJTHUIJSEN

Introduction

The achievable performance of mechatronic positioning systems is facing limitations in the current state-of-art design paradigm. To meet future requirements on production speed, quality and cost, it is envisaged that a significant increase is required in the complexity of positioning systems. This leads to the manifestation of increasingly complex system behaviour. Examples include increasing numbers of motion axes, the presence of flexible dynamical behaviour in the control bandwidth and the associated coupling between axes, and increased susceptibility to disturbances from multiple physical domains such as friction, hysteresis, thermal effects, acoustics, noise from electronics, etc.

Mechatronic system design approaches typically focus on excellent electromechanical designs [1], which subsequently simplify control design. It is envisioned that this design paradigm will become infeasible, e.g., due to excessive cost of materials with favourable (thermo-)mechanical properties. Hence, the foreseen trend of increasing system complexity motivates to reconsider the holistic system design process, which ranges from sophisticated electromechanical designs to intelligent control and software solutions.

On another hand, explosive progress has been made in the field of machine learning (ML) over the past decades. Spurred by the availability of data and low-cost computation [2], this has led to astounding results in complex applications, for instance achieving superhuman performance in Go and Atari games [19]. Moreover, these results are achieved without any prior knowledge of the environment dynamics.

This raises the question what ML has to offer for high-tech positioning equipment, and in particular how exploitation of ML techniques can enable a revolution in dealing with the increasing system complexity during the holistic mechatronic system design process. Indeed, a huge performance potential seems readily attainable, as both data and computing power are abundantly available in high-tech mechatronic systems.

However, there is a fundamental difference between the presented examples of ML applications [19] and high-tech positioning systems: interaction with the physical world. Without interaction with physical systems, there need to be only mild requirements on the training process, i.e., required training time and convergence properties. Conversely, mechatronic applications, where interaction with the physical world is pivotal, have very strict requirements on the training process.
Most successful ML applications to mechatronic systems (for example, drone racing [5], tokamak plasma control [6], stratospheric balloon navigation [7], and bipedal robot soccer [8]) mitigate these challenges by training the ML algorithm in a simulation environment. However, the resulting control performance is directly determined by the quality of the system knowledge that is used to build the simulator. Especially in view of the foreseen increasing system complexity of high-tech positioning equipment, this excessive modelling burden is undesired.

The aim of this article is to explore opportunities and challenges associated with ML for high-tech motion-control applications. Successful adoption of ML imposes a unique set of requirements, since high-tech manufacturing machines are cyber-physical systems that interact with the real world, and machine downtime has a huge impact

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on their economic value. In [3], it is argued that the learning on the physical system:

- shall be fast, since dedicated training experiments lead to production loss and fast adaptation is desirable in case of varying operating conditions, such as temperature changes due to internal dissipation and environmental variations;
- and shall be safe, since damage to the machine is in general unacceptable.

In the next section, we outline our view on the implications of these requirements on appropriate design of ML-based approaches for control. In the subsequent section, we present a range of suitably designed solution approaches that vary in their use of prior knowledge, ranging from data-enhanced yet dominantly physics-motivated control designs to more black-box-oriented ML controllers. Each technique is illustrated through a case study of an application at Sioux Technologies.

Machine learning for motion control

Machine learning is not so easy to apply in industrial practice of motion control due to the many decisions that need to be made, and since the impact of these decisions on the posed motion-control requirements is often unclear: what controller architecture, structure and complexity should be chosen, how the controller should be trained, how learning efficiency and safety can be guaranteed, etc.

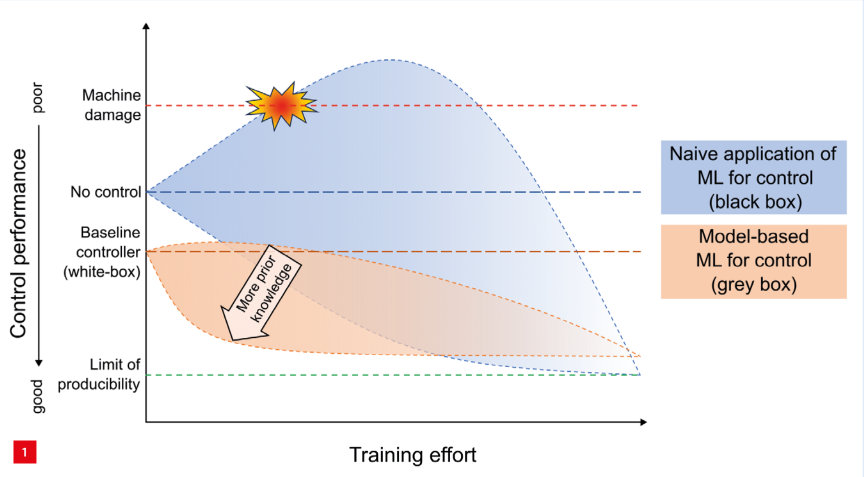
For example, neural networks are extensively in use as black-box function approximators in ML, but to control engineers they are unsatisfactory due to the difficulty in interpretation and lack of guarantees on learning speed and safety. In this section, we present insight into several aspects that contribute to successful applications of ML to motion control.

Role of prior knowledge

The central hypothesis in this article is that the judicious use of prior knowledge is pivotal for successful application of ML in motion control, as it can accelerate and safeguard the learning process. This is illustrated by Figure 1:

- *Black-box:* ML approaches do not use prior knowledge and typically require excessive training effort, i.e., the learning is slow. Additionally, the stability of the learning process is difficult to guarantee, i.e., the learning is not guaranteed to be safe.
- *Grey-box:* model-based ML approaches make explicit use of both data and prior knowledge and can lead to faster learning with guarantees on stability and performance.

In the next paragraphs, we discuss in what ways prior knowledge can be embedded in ML for motion control. In particular, the following essential elements are discussed: the selected controller structure, the used learning algorithm, and the data used for training.



The central statement in this article is that the judicious use of prior knowledge (e.g. models) in machine-learning algorithms is fundamental for successful applications in motion control, as it can accelerate and safeguard the learning process. Naive application of ML techniques to motion control often leads to unsatisfactory results, including machine damage.

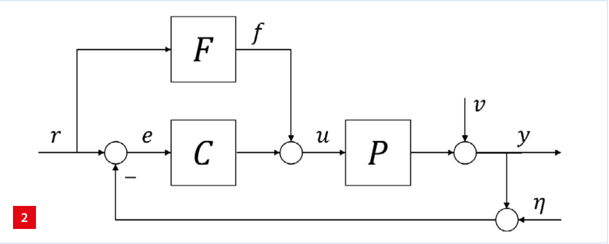
Control structure

Physics-based information can be directly employed in the control structure. The main point here is that domain-specific engineering knowledge that has proven itself during the last decades should be appropriately retained. Consider the control architecture shown in Figure 2 that is typically used in the motion-control domain. Here, P is the system to be controlled, and C and F are the feedback and feedforward controllers. The servo error e can be represented as:

$$e = S(I - PF)r - Sv - S\eta$$

This equation features sensitivity function $S = (I + PC)^{-1}$, motion reference signal r, and actuator and measurement disturbance signals v and η, respectively. Since the goal of feedback control is to attenuate disturbances v and η, feedback controllers are often tuned based on characterisations (models) of these disturbances. Feedforward controllers are typically designed based on knowledge of the inverse system dynamics, since the reference r is perfectly tracked if $F = P^{-1}$. Industrial practice is to design the feedforward controller as a low-order physics-based approximation of the inverse system dynamics. Using Newton's second law, for instance of the form:

$$m\frac{d^2y}{dt^2} + b\frac{dy}{dt} + ky = u$$



Typical motion-control architecture.

FUTURE-PROOF DESIGN PRINCIPLES FOR PRECISION MECHATRONICS

An initiative to produce updated design principles for precision mechatronics has been developed by the professors of precision engineering and mechatronics at the three Dutch universities of technology in association with DSPE, and in close collaboration with the Dutch high-tech industry. Building on the legacy of Wim van der Hoek, the Dutch doyen of design principles, the aim of the initiative was to collect over 100 cases that demonstrate the proper application of contemporary design principles. Many cases are already presented on a dedicated website and a broad selection will be collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

The Dutch school of design principles for mechanical precision engineering originated in production mechanisation at Philips. In the 1950s and 1960s, production mechanisation generally concerned machines for assembling discrete products, such as electron tubes or semiconductor components, often with feeding, positioning and fixing processes, requiring accuracies of 1 micrometer or better at speeds of 2,000 to 3,000 products per hour. To gain a competitive advantage, better control was needed to improve positioning accuracies and increase production speed.

It prompted Wim van der Hoek to focus on the dynamic behaviour of cam mechanisms. He had started working at Philips in 1949 after having studied Mechanical Engineering in Delft (NL) and was appointed part-time professor of Design and Construction at Eindhoven University of Technology (NL) in 1961.

Through his work, Van der Hoek gained insight in the disastrous effect of backlash in a machine on the accuracy of movement and positioning, all under the dominant limitation of a mechanism's natural frequency (the first eigenfrequency). It helped him to predict the contribution of dynamics to positioning errors in a mechanism. It also resulted in qualitative and quantitative insight into the mechanical design measures that had to be taken to control these positioning errors. 'Stiffness' instead of 'strength' became the leading design paradigm.

The Devil's Picture Book

Van der Hoek included all this in his lecture notes and, in addition, started to collect examples of good and bad precision-engineering practices in "The Devil's Picture Book" (*Des Duivels Prentenboek*, DDP). These cases were primarily intended as an invitation to engineers to consider their work in terms of design principles and, if possible, improve upon their designs.

The first topic in DDP was realising lightweight structures with high stiffness in order to raise the eigenfrequency of mechanisms in fast-moving machines; the second was avoiding backlash. The collection was soon extended to other topics: elastic elements, degrees of freedom, manipulation and adjustment, friction and hysteresis, guiding belts and wires, and energy management. Thus, Van der Hoek laid the foundations for the design principles for accuracy and repeatability. Table 1 gives an overview of these principles and their evolution.

Evolution

In the last decades of the previous century, the design of mechatronic devices and machines such as CD players and lithography machines has raised the bar. To meet their challenging specifications, thermal effects had to be addressed more extensively and new design concepts were introduced, such as 'virtual' servo stiffness, 'zero' stiffness, dual-stage configurations, and mass balancing.

Driven by Moore's Law, mechatronic design rose to new levels of sophistication in the 21st century. This urged the design community to question established design principles, such as minimisation of hysteresis. The demand for ever-higher control bandwidths could no longer be fulfilled only by lightweight and stiff design. Therefore, passive damping became a new design paradigm to further improve performance.

Just as revolutionary was the embracing of 'forbidden' over-actuation, which was needed to avoid excitation of internal mode shapes. Thus, design for symmetry became key, which required, for example, additional force actuators on actuated

Table 1
Overview of the design principles for accuracy and repeatability, as of ~1970, and their evolution, as of ~2000 (in green) and ~2010 (in red).

	Design principle	Implementation
1	Kinematic design	• Exact constraints • Mechanical decoupling via flexures and elastic hinges
2	Design for stiffness	• Structural loops with high static stiffness and favourable dynamic stiffness
3	Lightweight design	• Design for low mass and high eigenfrequencies
4	Design for damping	• Energy dissipation that slows down motion without introducing position uncertainty
5	Design for symmetry	• Symmetry in geometry and external loads • Over-actuation
6	Design for low friction and hysteresis	• Minimisation of friction and virtual play in high-precision structures, connections and guideways
7	Design for low sensitivity	• Thermal centre and thermal (compensation) loops with high stability • Low-expansion materials • Isolation of disturbances, e.g. via isolated metrology loop • Offset minimisation, e.g. Abbe principle and Bryan principle, and drive-offset minimisation relative to the centre of mass • High-bandwidth feedback control
8	Design for stability	• Minimisation of heat dissipation and microslip in interfaces • Minimisation of material creep and drift
9	Design for load compensation	• Weight compensation, reaction force compensation and (parasitic) stiffness compensation • Position-dependency compensation
10	Design for minimal complexity	• Balancing and hence minimisation of complexity and related cost via a multidisciplinary system approach

wafer chucks. This does not introduce significant uncertainty as long as the actuator stiffness remains small.

The design of more powerful actuators, for instance (variable) reluctance actuators, also posed new challenges, such as nonlinearity and position dependency, which required new control and calibration strategies. The focus of control shifted from the time to the frequency domain, i.e. from creating a favourable time response to shaping frequency-response functions for robust controller design with good performance.

Update required

As well as an evolution of design principles, there was also a succession of textbooks published over the years, by Rien Koster, Herman Soemers and, recently, Susan van den Berg, who has brought design principles education in a didactically sound manner to the higher vocational education level.

In 2020, it was concluded that a new update was required for the body of design principles. The initiative originated from the precision engineering and mechatronics departments at the Dutch universities of technology – Delft, Eindhoven and Twente – in association with DSPE. The idea was to produce an up-to-date overview of the design principles for precision mechatronics in close collaboration with the Dutch high-tech industry. Building on the legacy of Van der Hoek's DDP, the aim was to collect over 100 cases that demonstrate the proper application of contemporary design principles.

The cases could be contributed by universities as well as companies. They should clearly illustrate actual themes in a manner that is comprehensible for a broader audience, both in industry and academia, and not cover a complete system. A large number of cases is already presented on the dedicated website and more cases are welcomed. A broad selection of cases will be collected in a new textbook, preceded by an extensive, in-depth introduction of the design principles.

WWW.DSPE.NL/KNOWLEDGE/DPPM-CASES

In 2020, DSPE published a book (in Dutch) about Wim van der Hoek, covering his career at Philips and Eindhoven University of Technology, his breakthrough ideas on achieving positioning accuracy and control of dynamic behaviour in mechanisms and machines, and their reception and diffusion.