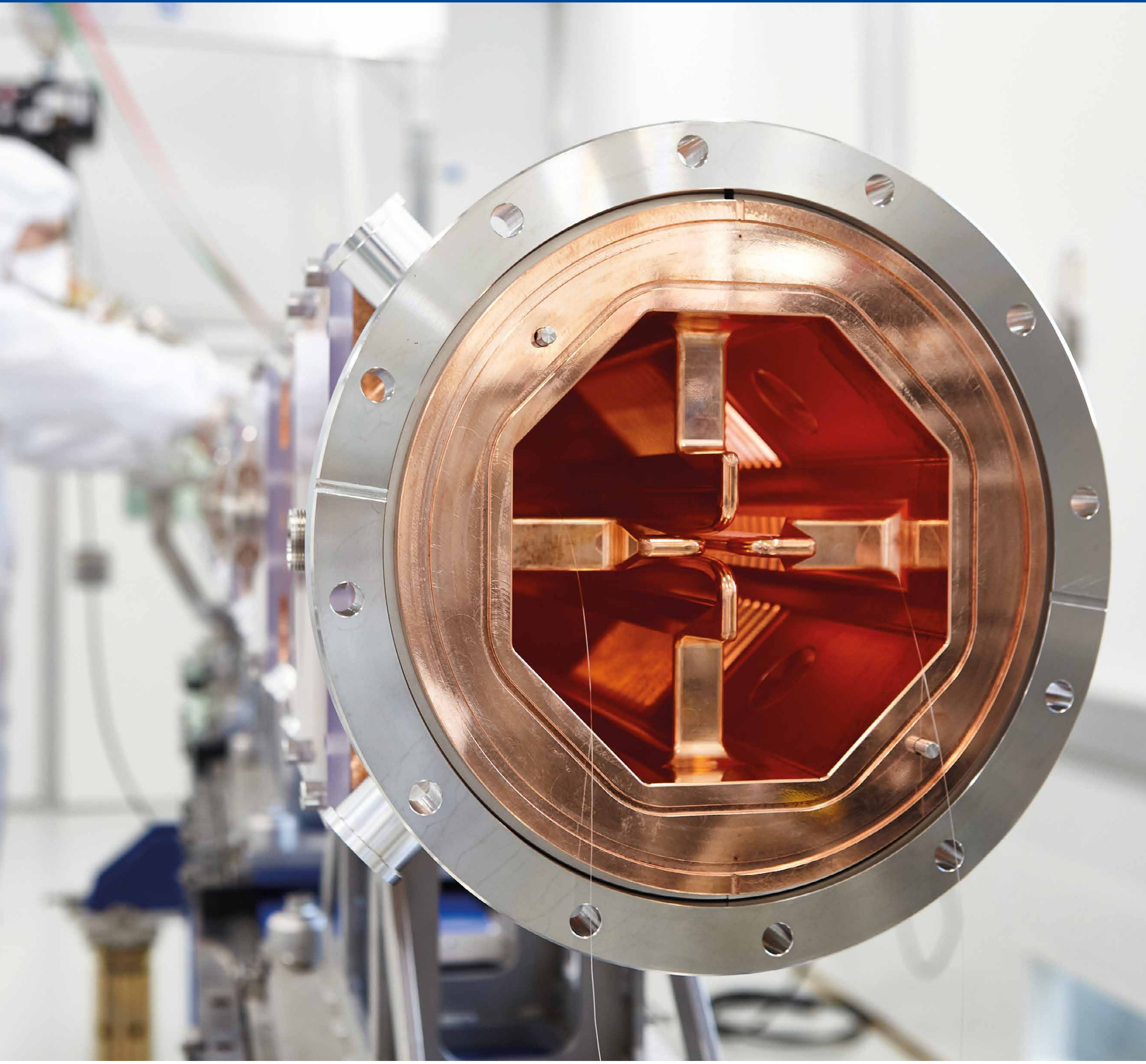
DSPE MIKRONIEK

2023 (VOL. 63) ISSUE 2

PROFESSIONAL JOURNAL ON PRECISION ENGINEERING



- THEME: SENSORS & ACTUATORS
- BEYOND INERTIAL MATCH FOR ACTUATOR AND TRANSMISSION SELECTION
- NANOMEASURING AND NANOPOSITIONING MACHINE/PLATFORM
- DSPE OPTOMECHATRONICS SYMPOSIUM 2023 REPORT

MIKRONIEK IS A PUBLICATION OF THE DUTCH SOCIETY FOR PRECISION ENGINEERING – WWW.DSPE.NL

PUBLICATION INFORMATION

Objective
Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics. The journal is read by researchers and professionals in charge of the development and realisation of advanced precision machinery.

DSPE
YOUR PRECISION PORTAL

Publisher
DSPE
Julie van Stiphout
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editorial board
Prof.dr.ir. Just Herder (chairman, Delft University of Technology),
Servaas Bank (VDL ETG), B.Sc.,
Maarten Dekker, M.Sc. (Philips),
Otte Haitsma, M.Sc. (Demcon),
dr.ir. Jan de Jong (University of Twente),
Erik Manders, M.Sc. (Philips Engineering Solutions),
dr.ir. Pieter Nuij (MaDyCon),
dr.ir. Ioannis Proimadis (VDL ETG),
Maurice Teuwen, M.Sc. (Janssen Precision Engineering)

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
+31 (0)40 – 251 99 29, info@snep.nl

Subscription
Mikroniek is for DSPE members only.
DSPE membership is open to institutes, companies, self-employed professionals and private persons, and starts at € 80.00 (excl. VAT) per year.

Mikroniek appears six times a year.

ISSN 0026-3699

The cover image (illustrating RI Research Instruments' development of normal conducting RF accelerators and pulsed systems) is courtesy of RI / Monika Nonnenmacher. Read the feature on page 21.

IN THIS ISSUE

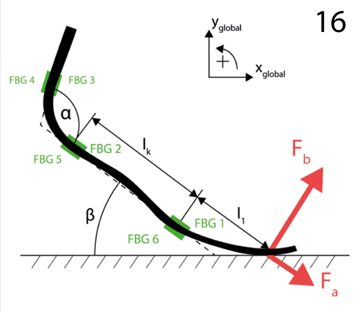
THEME: SENSORS & ACTUATORS

05
Beyond inertial match
In high-dynamic mechatronic systems, the inertial match principle is a widespread concept used to assist with actuator and transmission selection. An extension of the inertial match principle is presented for applications where the payload is subject to a constant force (such as gravity) or friction.

12
Combining sensors and interferometers
A nanomeasuring and nanopositioning machine/platform can be combined with an atomic force microscope, an optical sensor or a microprobe. This combination can be used to perform high-precision free-form surface measurements as well as three-dimensional scanning and tactile measurements on microcomponents.

16
Measuring ground reaction forces in running-specific prostheses
A measurement system for running-specific prostheses has been developed. It uses Fiber Bragg Grating sensors to measure the strain in the prosthesis, from which the ground reaction forces can be calculated.

22
Low yet relevant
For the reliable measurement of low gas concentrations, VSL produces primary reference materials to calibrate the equipment used. VSL operates laser spectrometers for analysing both the primary reference materials and the pure gases used for their preparation. In-house developed instruments are presented, as well as some applications.



27
Event report – DSPE Optomechatronics Symposium 2023
The successful symposium featured fascinating presentations about the progress in optomechatronics. This ranged from EUV mirror metrology and pellicle qualification to digital pathology system design and photonics assembly platform development.

FEATURES

04 EDITORIAL
DSPE president Hans Krikhaar on smart metrology: Sense, collect, analyse, learn, improve, act and admire!

TAPPING INTO A NEW DSPE MEMBER'S EXPERTISE
15 Somni Solutions – reliable, high-precision fibre-optic sensors.
21 RI Research Instruments – from conception to completion.
34 TCPM – complete and robust total solutions.

32 DSPE
Including: Volunteer in the spotlight, Gabby Aitink-Kroes.

35 UPCOMING EVENTS
Including: euspen's 23th International Conference & Exhibition.

36 ECP2 COURSE CALENDAR
Overview of European Certified Precision Engineering courses.

37 NEWS
Including: 30th anniversary IBS Precision Engineering

SENSE AND COLLECT, ANALYSE AND LEARN, IMPROVE AND ACT, AND ADMIRE

Almost every young child has experienced the pain (sensing) after touching (acting) a heater. It subsequently learned not to touch hot objects by sensing before acting. Sensing, learning and acting makes you more intelligent.

The same is of course the case for the systems we design. A good strategy for sensing and acting makes systems more efficient. Collecting data and using them to improve the next actions makes systems even more intelligent. This all sounds very simple, however in practice we are not always smart enough in how we use sensor technology and metrology.

Last year, in the Techcafé (the new DSPE-Mikrocentrum collaboration) about robotics, I learned that buying a robot still entails several months of cumbersomeness before it becomes operational. Motor babbling can be a way to improve the installation of robots: by learning from the previous action, the next action can be improved, in the same way as a baby learns to speak by just babbling and uses its legs and arms by trial & error.

A capacity sensor can sense the presence of material. A camera can do the same, but can detect much more and later even more when the software has been updated. For example, intelligent camera systems are being introduced in agriculture, often in combination with artificial intelligence (AI). When a weeding robot makes a mistake, a specialist can show the plant concerned to the robot indicating “You should not weed this!”

Using such an AI system, the human specialist teaches a robot to improve its skills. The same applies to the world of mechatronics, where Intelligent Learning Control is a method that learns to improve control by measuring the result of the previous control action and feeding this it into its algorithm.

In the Netherlands, the famous singer Ramses Shaffy scored a hit with *“Zing, vecht, huil, bid, lach, werk en bewonder”* (Sing, fight, cry, pray, smile, work and admire). We could make a smart metrology version of it: Sense, collect, analyse, learn, improve, act and admire!

Hans Krikhaar
President of DSPE and program manager Fontys Engineering Master System Design
hans.krikhaar@dspe.nl

BEYOND INERTIAL MATCH

In high-dynamic mechatronic systems, the inertial match principle is a widespread concept used by engineers to assist with actuator and transmission selection. Inertial match describes the optimal transmission ratio between payload and actuator inertia for minimum peak current and minimum thermal dissipation, where the effective inertia of the payload due to the transmission ratio is equal to the inertia of the actuator. This article presents an extension of the inertial match principle, for applications where the payload is subject to a constant force (such as gravity) or friction. Unlike the classical inertial match case, two different optimal values are now found, one for minimum peak current and one for minimum thermal dissipation.

RON DE BRUIJN

Introduction

In the early development phase of a mechatronic system, it is valuable to define a range of possible actuators and transmissions for the specific application. Inertial match is a principle that can help here, by defining the transmission ratio for minimum peak force/torque and minimum thermal dissipation.

This article starts with the description of a simplified mechatronic system and the relevant physical relations. Secondly, a refresher of the classical inertial match is presented, followed by an extension of the inertial match principle for applications with a payload subject to a constant force. The optimal transmission ratio values for minimum peak current and minimum thermal dissipation are extensively discussed, followed by guidelines to assist with actuator selection. Finally, friction effects are included, followed by some concluding remarks.

Relevant physical relations

The force/torque that a Lorentz-type actuator (e.g., a voice-coil actuator or a DC motor) can deliver is linearly dependent on the current: $F = KI$ or $T = KI$, with F and T the actuator force and torque, respectively, K the motor constant in [N/A] or [Nm/A], and I the current, meaning that minimum current is equivalent to minimum force/torque.

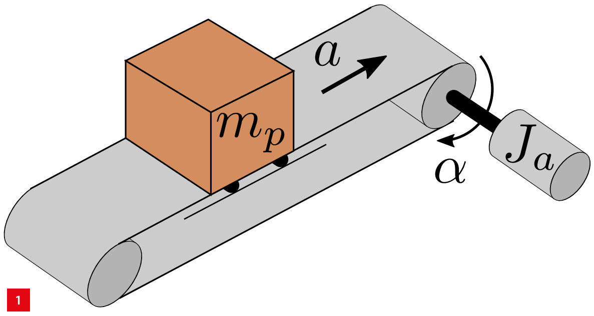
The maximum rms current applied to an actuator is limited by the allowable thermally dissipated energy W_{th} ($= \int RI(t)^2 \mathrm{d}t$), which is proportional to either $\int F(t)^2 \mathrm{d}t$ or $\int T(t)^2 \mathrm{d}t$, with R the electrical resistance of the actuator. The dissipated energy is proportional to the force/torque squared and the time the force/torque is acting.
The allowable thermal dissipation is determined by a combination of the maximum temperature of the actuator coil, the environment, the cooling method (air, water, etc.) and the mechanical design, which determines the thermal time constant that depends on the thermal resistance and thermal capacity of the actuator [1].

Maximum peak current of a power amplifier limits the peak force/torque an actuator can deliver. High peak currents in combination with other power amplifier requirements (noise level, linearity, dynamic properties, slew rate, etc.) can limit the availability of suitable power amplifiers significantly [2].

The transmission ratio between actuator and payload should be selected such that the peak current and thermal dissipation are minimised. Here, a simplified system is used to explain the inertial match concept and the effect of a payload subject to gravity on the inertial match criterion.

The example here consists of a payload mass (m_p = 1 kg) that is translated from one position to another with a rotational actuator, in this case a DC motor (J_a = 1,000 gcm^2). The rotational motion is converted with pulleys and a belt to a translational motion, see Figure 1. The transmission ratio of this system is defined as:

$$i \equiv \frac{motion\ out}{motion\ in}\ [\mathrm{m/rad}] \qquad (1)$$



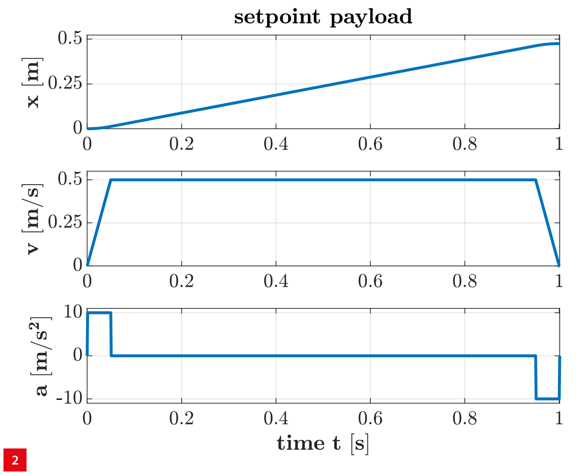
1

Simplified mechatronic system in which a rotary actuator with inertia J_a is accelerating a payload mass m_p via a rotary belt.

AUTHOR'S NOTE

Ron de Bruijn is a Ph.D. candidate in the Control Systems Technology (CST) group at Eindhoven University of Technology (TU/e). At the TU/e, he has been teaching courses related to mechatronic design and design principles, which provided inspiration for this article. He acknowledges the fruitful discussions about inertial match with his fellow Ph.D. candidate Sander Hermanussen, his supervisor Hans Vermeulen and the other colleagues from the Design for Precision Engineering lab.

r.g.c.d.bruijn@tue.nl
www.tue.nl/cst



2

Second-order setpoint for the simplified mechatronic system with displacement x, velocity v and acceleration a. Note that the acceleration/deceleration time here is small compared to the total setpoint time.

Note that the approach of this article also holds for motion systems with a transmission from translational to translational motion, or rotational to rotational motion (both with a dimensionless transmission ratio), and from translational to rotational motion (transmission ratio unit: [rad/m]). Rotational quantities (torque, moment of inertia, angular displacement, angular velocity, angular acceleration, etc.) can be replaced by translational quantities (force, mass, displacement, velocity, acceleration, etc.) and vice versa, depending on the mechatronic system. In this example, imperfections such as finite belt stiffness and play are neglected. Friction will be neglected at first and then discussed in a separate section.

Figure 2 shows the prescribed setpoint of the payload. The force required to move the payload according to Newton's Second Law is: $F_p = m_p a$. Here, F_p is the required force, m_p the payload mass and a the required payload acceleration. The force and resulting acceleration are delivered with the rotational actuator as: $F_p = T_p/i$ and $a = \alpha i$. Here, T_p is the actuator torque to move the payload and α the actuator angular acceleration to give the payload the desired acceleration. Combining the required payload force with the actuator relations results in: $T_p = m_p i^2 \alpha$. The moment of inertia of the payload as experienced at the actuator shaft is defined as: $J_p = m_p i^2$.

Classical inertial match

The classical inertial match criterion describes the optimal transmission ratio for minimising the torque required for acceleration. Imperfections are neglected, so torque is only required during acceleration. The minimum peak torque T in this case also corresponds to the minimum thermal dissipation, because only during acceleration energy is dissipated and this dissipation is proportional to T^2. The total moment of inertia (J_t) the actuator needs to accelerate, is the moment of inertia of the rotating part of the actuator itself (J_a), and the effective payload moment of inertia as described above: $J_t = J_a + m_p i^2$. The setpoint defines an acceleration a for the payload and, combined with the transmission ratio, this results in an angular acceleration of the actuator $\alpha = a/i$. The required torque is:

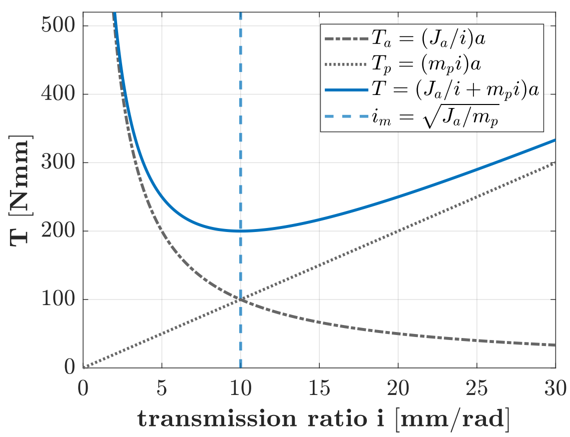
$$T = J_t\alpha = \left(J_a + m_p i^2\right)\frac{a}{i} = \left(\frac{J_a}{i} + m_p i\right)a \tag{2}$$

To find the optimal inertial match transmission ratio i_m, the required torque is differentiated to i and the derivative is set equal to zero:

$$\frac{dT}{di} = 0 \rightarrow i_m = \sqrt{\frac{J_a}{m_p}} \tag{3}$$

This optimal transmission ratio yields a minimum peak torque, resulting in minimum peak current and minimum thermal dissipation. Note that this does not minimise the mechanical power or kinetic energy delivered to the total system: a larger transmission ratio will always reduce the kinetic energy in the system by reducing the kinetic energy of the actuator, as the payload kinetic energy is determined by the setpoint.

Figure 3 shows the torque component required to accelerate the actuator moment of inertia T_a, the torque component to accelerate the payload T_p, and the total required torque T; see also the corresponding terms of Equation 2. When both terms are equal, the total required torque is minimum. In Figure 4, the setpoint of Figure 2 has been converted to actuator quantities for three different transmission ratios ($0.5i_m$, i_m and $1.5i_m$). The actuator torque is lowest for the transmission ratio with inertial match.



3

Torque terms to accelerate the actuator moment of inertia (T_a) and the payload mass (T_p), respectively, and the total torque (T), as a function of the transmission ratio i.

COMBINING SENSORS AND INTERFEROMETERS

A nanomeasuring and nanopositioning machine/platform, in combination with an atomic force microscope, an optical sensor or a microprobe, can be used to perform high-precision free-form surface measurements as well as three-dimensional scanning and tactile measurements on microcomponents. Uncertainties in the nanometer range are achievable, and the use of laser interferometers for position measurement allows traceability of measurements for the purpose of sensor calibration.

DENIS DONTSOV, ENRICO LANGLOTZ AND ILKO RAHNEBERG

AUTHORS' NOTE

Denis Dontsov (CEO), Enrico Langlotz (project manager) and Ilko Rahneberg (CTO) are all associated with SIOS Meßtechnik, located in Ilmenau (Germany). SIOS has been developing and manufacturing laser-interferometric and other precision measuring instruments for calibration and nanometrology for measuring length, angle, vibration, straightness, mass, force and other metrics at high resolutions with low measurement uncertainty for over 30 years.

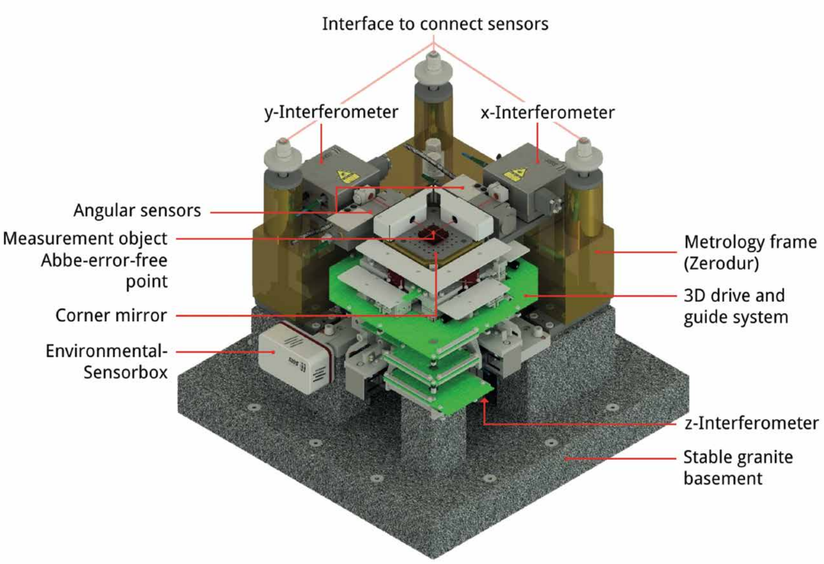
contact@sios.de
www.sios-precision.com

Introduction

The ability to perform nanometer-precision metrology is increasingly influencing all phases of product development and manufacturing, from design engineering, prototyping and manufacturing to quality control, process analysis and final inspection of components and assemblies. Examples include prototyping, quality control, process analysis and final inspection of components and assemblies. The shape and dimensions of workpieces, optical components and surfaces also require high-precision metrology equipment.

Metrological concepts for nanopositioning

Laser interferometry is a commonly used technology when the metrological aspect of the measurement is the focus of the application. In addition to high resolution, laser interferometers offer the possibility of metrological traceability of the length information to the international standard. Their theoretical resolution can be achieved in the range of a few picometers, but in practice this can only be realised in special arrangements [1]. The most important feature of single-beam laser interferometers therefore, in contrast to linear scales, is the ability to realise Abbe-error-free measuring arrangements.



1

Concept of the nanomeasuring and nanopositioning machine NMM-1.

One of the critical parameters of any nanometrology measurement set-up is its long-term thermal stability. Since the measurement can be performed over several hours, the influence of thermal drifts on the measurement set-up should be avoided. Two different approaches can be realised in practice, with measurement set-ups based on either an ultra-stable measurement frame or an ultra-stable differential interferometer.

The first approach, based on an ultra-stable metrological frame, has been successfully realised in the nanomeasuring and nanopositioning machine NMM-1. The device has a Zerodur metrological frame as the basis for the positioning feedback sensors as well as the probing systems. The main advantage of the compact set-up is a clear definition of the thermal behaviour of the system. However, extending the measurement range will increase the cost of the metrology frame.

The second approach is only possible if laser interferometers with a thermally perfect qualification can be used, which enables compensation of refractive index and thermal drifts by a differential principle. They can be mounted on a thermally unstable base if they work against an external reference point. This approach has been followed in the nanopositioning platform NPP-1, of which the architecture is scalable and can be applied for different positioning ranges.

Nanomeasuring machine NMM-1

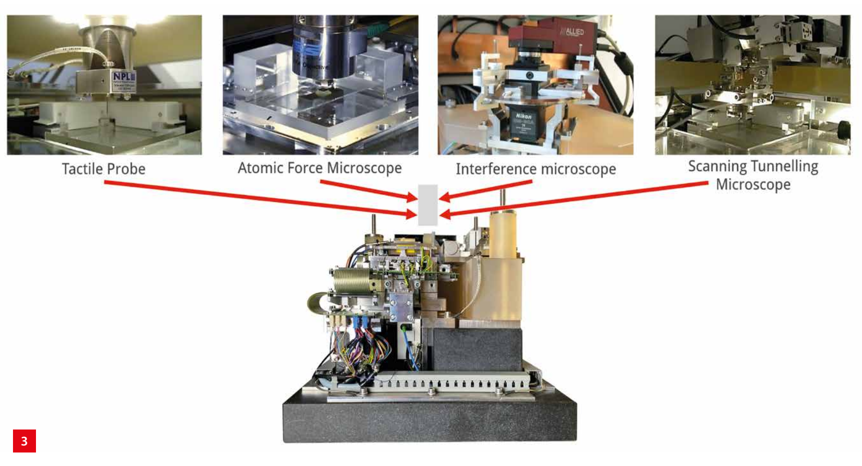
The nanomeasuring and nanopositioning machine NMM-1 from SIOS Meßtechnik is a 3D measuring device with an open sensor architecture that realises an Abbe-error-free measuring arrangement in the three positioning axes x, y

and *z* [2] [3]. The laser interferometers are mounted on a long-term stable metrological base and all three beams intersect at the virtual measuring point, where the probe point of the mounted sensor is located. Figure 1 shows the measurement set-up of the NMM-1.

The high-accuracy mirror corner of the NMM-1 forms the coordinate system for the instrument and is positioned over the laser interferometer readings with sub-nanometer accuracy over the entire 25 mm x 25 mm x 5 mm measurement volume. Figure 2 shows the capability of the positioning system in closed-loop mode.

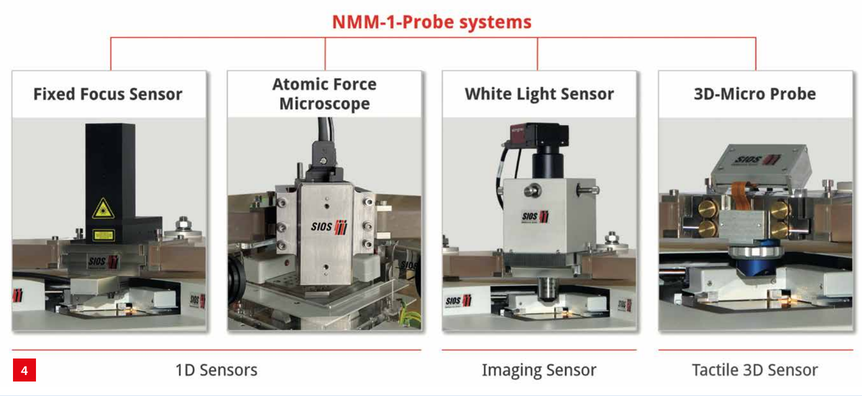
Probing sensors can be calibrated in-situ on the NMM-1 by built-in laser interferometers and controlled to a fixed setpoint throughout the measurement. This allows the sensors to be used with a small measuring range, so that only the smallest controller deviations are recorded during the measurement. Therefore, the laser interferometers, which form the metrological basis for the measurement result, are decisive for the measurement uncertainty.
The measured value is the combination of the sensor value and the laser interferometric measurement.

The high positioning accuracy of the NMM-1 provides the basis for metrological measurements, while the open hard ware architecture allows the NMM-1 to be used as a calibration platform for basic research and sensor development. Figure 3 shows several examples of sensors that can be easily calibrated on the NMM-1 platform. The sensors to be calibrated must have either analog outputs or a synchronisable interface. The acquisition of the sensor data is done simultaneously with the interferometer readings with a high sampling frequency and all measurement data can be stored immediately on the main computer.
Depending on the sensor used, different measurement tasks can be accomplished. Figure 4 shows the range of standard sensors that can be used with the NMM-1. Surface scans can be conducted with an optical single-point LFS fixed focus sensor, and when using an atomic force microscope line scans can be performed according to the described control principle over several millimeters with highest lateral resolution.



3

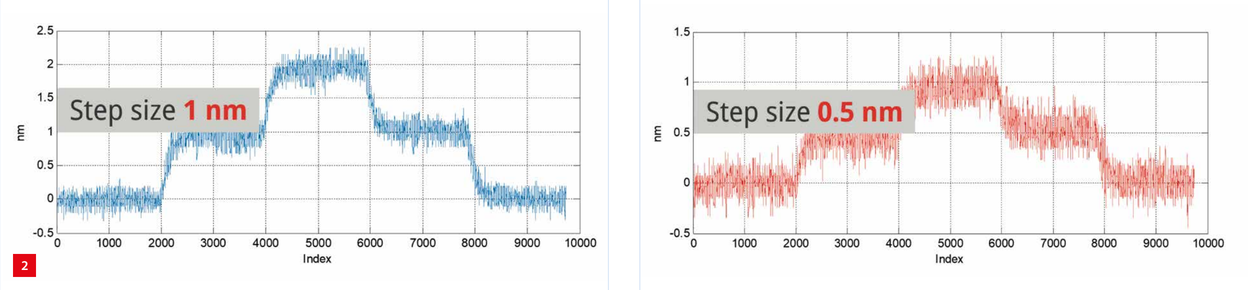
NMM-1 positioning platform for the calibration of various sensors.



4

Various probing systems for the NMM-1.

The biggest challenge is the 3D measurement on the NMM-1 with a microprobe. The 3D probe transforms the NMM-1 into a nano-CMM (coordinate measuring machine), where all problems of a CMM regarding the interaction with the measuring surface also apply to the NMM-1. The use of 3D microprobes for nanometer-accuracy measurements requires special care in selecting the probing strategy. Due to the small diameter of the microprobe's stylus ball and the low probing force, surface effects of the target have a greater influence on the measurement result than with macroscopic styli. Examples include surface roughness, ball flattening, plastic deformation of the target surface, and wear. The probe can be calibrated in-situ on the NMM-1.



2

Positioning stability performance of the NMM-1 positioning stage, for step sizes of 1 nm and 0.5 nm, on the left and right, respectively: measured position (variation) for a long series of measuring points (denoted by Index).