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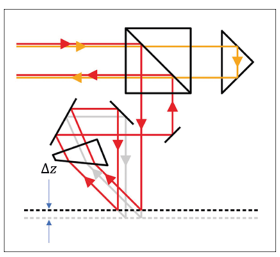

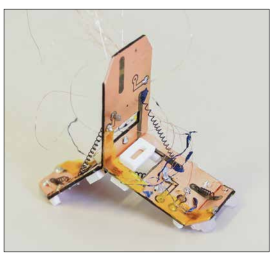

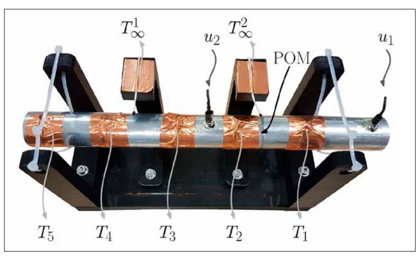

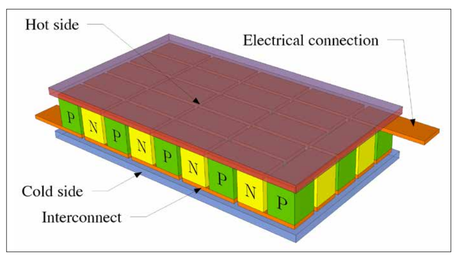

- THEME: THERMAL CONTROL
- ENCODERS GRADUATING TO EXTREME PRECISION
- COBOTS: NO FAIRYTALE CHARACTERS
- MULTITASKING MACHINES

DSPE

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DSPE
YOUR PRECISION PORTAL

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The main cover photo (featuring a Thermo Fisher Titan electron microscope outside an opened acoustic enclosure) is courtesy of Thermo Fisher (photo: Leo Koomen). Read the article on page 12 ff.

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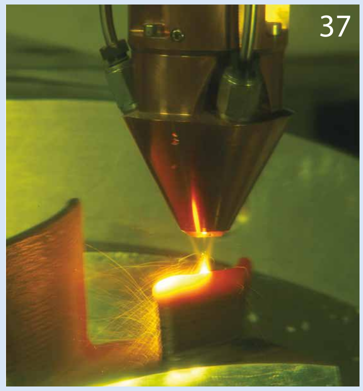
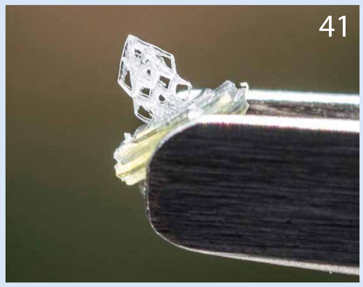
THEME: THERMAL CONTROL





FEATURES

IN CONTROL OF THERMOMECHANICS, IN SEARCH OF KNOWLEDGE AND COMMUNITY

Thermomechanics is one of the disciplines that is crucial for successfully designing precision systems, especially optical systems. Thermal loads always lead to drift, which can 'ruin' precision. Hence, thermal control is needed to safeguard these systems' precision performance.

Several industry trends are increasing the relevance of thermomechanics: the demand for higher throughputs in production processes is fuelling an ongoing quest for sources, like lasers or the EUV source, with higher power, while alternatively, the demand for higher accuracies requires more stable systems exhibiting less drift – or at least drift behaviour that is more predictable, for incorporation into thermal control. A third trend for which thermomechanics is highly relevant is the increasing demand for extreme environments, like vacuum or cyrogenics, which are often required for taking the next step in research or making new industrial applications possible.

In response to these considerations, eight years ago DSPE initiated a Special Interest Group (SIG) on thermomechanics. One of the things we found was that what information there was on the internet concerning thermomechanics was limited. With DSPE being what it is, an organisation by engineers for engineers, the SIG set out to gather and present information on thermomechanics in a structured way on the DSPE website.

Over a two-year period we created a website with 60 pages of content on modelling, analysis and measurement. We focused on practical usability, so the website offers calculators, rules of thumb, relevant material data, links and articles. Since the release of this 'thermomechanics website', half of the visitors to the DSPE website (47,000 annually) specifically target the thermomechanics pages. Currently, we are working on an update of this substantial knowledge base.

The success of this thermomechanics corner resulted in DSPE deciding to extend its website with additional relevant and unique knowledge for precision engineers, on subjects like 'dynamics for precision' and vacuum technology. In general, we all recognise the fact that engineers searching on the internet for specialist items only find limited knowledge. Google or any regular search engine will give an answer, when it concerns standard knowledge, in just a split second; however, when looking for specialist knowledge, one can be lost for hours on the internet without finding the right information.

Therefore, we are going to work on a better search facility for precision engineers, using expertise including artificial intelligence and data mining. This will help engineers to improve their research or product development process, while also lead to strengthening the virtual community of precision engineers.

We invite all our readers to help generate the content we all need, as well as to assist in working on the DSPE website and to come up with ideas for building a virtual community of precision engineers. Sharing and collaborating are among the strengths of our industry – and most certainly of DSPE.

Pieter Kappelhof
Technology manager Hittech Group, vice president DSPE
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PELTIERS FOR PRECISION ACTUATION

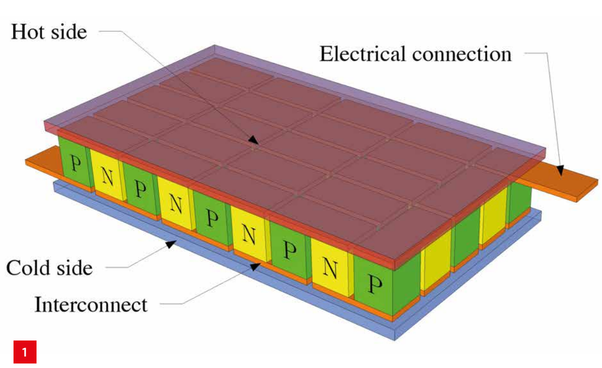
Peltier elements, i.e. thermo-electric coolers, are attracting more and more attention for application in high-precision systems where they enable active heat exchange and sub-zero [°C] thermal conditioning. Linear or switching PID controllers are commonly used for their control because of their simplicity in both design and implementation. However, due to their nonlinear behaviour, controlling the cold-side temperature of peltiers isn't simple. As such, Philips Innovation Services investigated a generic input-output linearising feedback law for Peltier devices, while explicitly modelling the effects that degrade the control performance in a practical set-up.

ROB VAN GILS

Introduction

Both consumer electronics and professional equipment alike are becoming increasingly reliant on precise thermal management. Challenges range from (air-only) high-heat-flux cooling, e.g. for increased efficiencies in high-power LED devices [1], to precise thermal conditioning of high-performance components, e.g. in handheld diagnostics platforms for the world's common diseases [2, 3]. As such, thermal control is gaining more attention in the design of these devices.

Peltier elements – or 'peltiers' – are thermoelectric coolers (TECs) that can be used either for heating or for cooling. Their main advantages compared to, e.g., a vapour-compression system are their lack of moving parts or circulating liquid, invulnerability to potential leaks, and their small size and flexible shape. This makes them ideal as thermal actuators. As a result, the devices are also gaining more attention for application in high-precision systems, where they enable active heat exchange and sub-zero [°C] thermal conditioning. The disadvantages of peltiers are their high cost, poor power efficiency, sensitivity to mechanical stresses and high currents.



1

Peltier (or thermoelectric cooler) schematic. (Source: michbich, Wikipedia, commons.wikimedia.org/w/index.php?curid=9076557)

TECs operate based on the Peltier effect, more commonly referred to as the thermoelectric effect. A Peltier device has two sides, connected by thermoelectric legs or pellets, i.e. pairs of N- and P-type semiconductors, which are placed thermally in parallel and electrically in series (see Figure 1). When a DC current flows through the device, it brings heat from one side to the other, so that one side gets cooler while the other gets hotter, generating a 'hot' and a 'cold' side. The hot side is attached to a heat sink so that it remains close to ambient temperature, while the cold side falls below room temperature, see for example [4].

Thermal control/actuation by Peltier devices has been investigated in a wide variety of studies [5]. Most of them focus on effective control of the Peltier cold side (see for example [6-8]). Mathematical models describing the thermal behaviour of Peltier elements can be found in among others [4, 5, 7].

Although various control strategies have been studied, the linear proportional-integral-differential (PID) controllers or switching PID controllers (i.e., where varying parameters are used, e.g. gain scheduling) are commonly used for their simplicity in both design and implementation [8]. However, due to their nonlinear behaviour, controlling the cold-side temperature of peltiers isn't simple. Linear PID control might work in some cases, but isn't robust (see [7]). On the other hand, other studies that consider nonlinear controller techniques don't take into account practical limitations in their controller design.

Therefore, this study investigates a generic input-output (IO) linearising feedback law for Peltier devices, while explicitly modelling the effects that degrade the control

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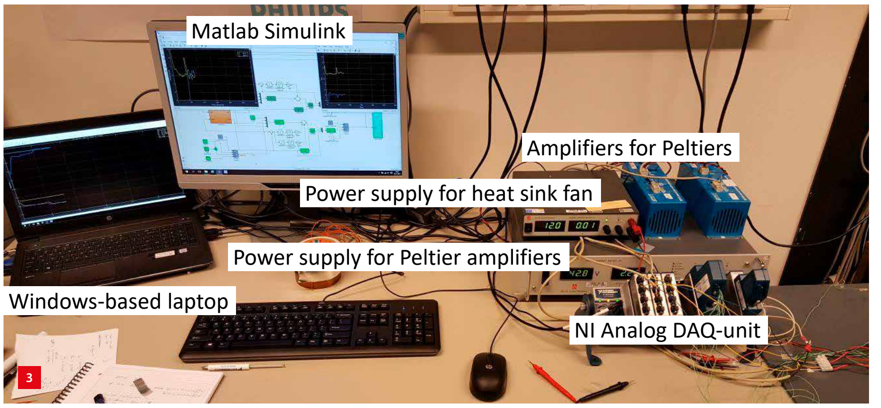
performance in a practical set-up. An IO linearisation scheme is a feedback law that introduces a new virtual input which relates linearly to the output, in this case the bottom plate temperature. This results in increased performance and larger robustness regimes (see also [9]).

Methodology

Experimental set-up
This study investigates the practical effectiveness of the IO linearising feedback law by means of a simple test set-up representative of part of a handheld diagnostic device. The set-up is shown in Figure 2. It consists of a stainless steel bottom plate that is divided into two sections that must be thermally controlled individually. To this end, two peltiers are placed between the bottom plate and the aluminium top plate. The latter is connected to a fanned heat sink (HS).

The set-up is controlled using a thermal control platform: a Windows-based computer running Matlab Simulink with software developed in-house to communicate with a USB-based National Instruments DAQ unit for importing and exporting signals (see Figure 3). The Matlab Simulink environment allows for quick and flexible controller design for every set-up. Moreover, it allows for the use of standard control theory due to the extensive systems control toolbox available in Matlab.

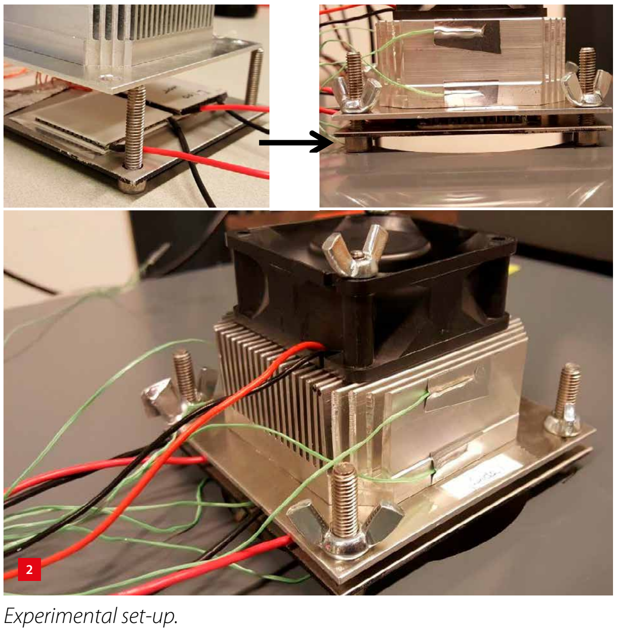
Thermo-dynamical model
In order to calculate appropriate controller settings, the experimental set-up is modelled using the Philips Advanced Lumped Mass (PALM) tool, i.e. a set of Matlab macros developed in-house to facilitate efficient lumped-mass modelling. Figure 4 presents a schematic overview of the model of the set-up. The top and bottom plate are divided into four masses each: two directly adjacent to the peltiers and one mass to represent the plate around each TEC. The HS is divided into a left and right side, and base and fins. The modelling details in connecting the lumped masses are omitted here since these masses can be simply connected via linear thermal resistances. Instead, only the mathematical relations describing the peltier thermal behaviour are discussed (see the box).



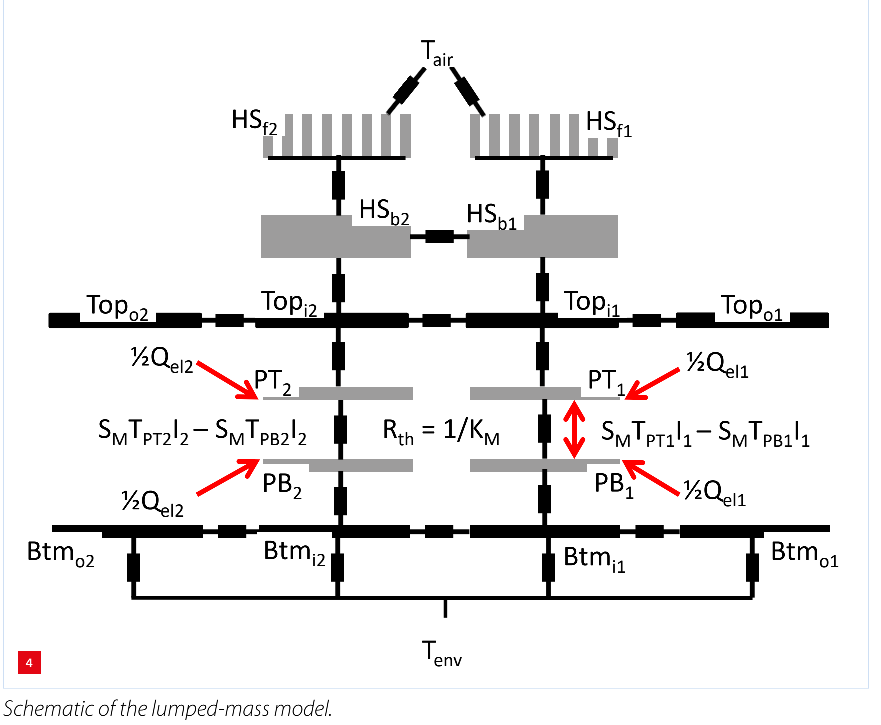
Data acquisition set-up.

Set-up identification and model validation

The temperature-averaged parameters for the peltiers considered are determined using the thermal control platform: $S_M = 0.0509$ V/K, $R_M = 3.34\ \Omega$, $K_M = 0.394$ W/K. The set-up contains two peltiers that can be actuated individually. To validate the model, both peltiers are subjected to different input currents and both the resulting peltier voltages as well as the cold-side temperatures are logged and compared to simulations.



Experimental set-up.



Schematic of the lumped-mass model.

CHALLENGES AND OPPORTUNITIES FOR SYSTEM IDENTIFICATION

Thermal effects are becoming increasingly important in efforts to enhance the performance of electron microscopes. Therefore, accurate thermal-mechanical models are desired for analysis and control. Modelling thermal systems from experimental data, i.e. system identification, is challenging due to large transients, large time scales, excitation signal limitations, large environmental disturbances, and nonlinear behaviour. An identification framework has been developed to address these issues. The presented approach facilitates the implementation of advanced control techniques and error compensation strategies by providing high-fidelity models.

ENZO EVERS, RONALD LAMERS AND TOM OOMEN

Introduction

Thermo Fisher is a leading manufacturer of electron microscopes. Their high-end (transmission) electron microscopes are developed and produced in Eindhoven (NL). These systems are capable of visualising objects at the atomic scale with a resolution down to 50 picometer (sub-Ångström resolutions).

The goal of an electron microscope is to acquire high-quality and high-resolution images of a specimen. The basic operation principle of an electron microscope, which is similar to that of a conventional light microscope or slide projector, is shown in Figure 1. Whereas a slide projector works with light and optical lenses, an electron microscope works with electrons and electromagnetic lenses.

A general overview of a transmission electron microscope is shown in Figure 2. The electron beam is generated inside the electron source, and the electrons pass through the condenser lens system, which makes the electron beam parallel. Then, the electron beam passes through a thin specimen that is mounted on a sample manipulation stage. This stage can move the specimen with respect to the electron beam, hence a large area of the specimen can be imaged. The corrector lens system is an additional module that can be placed on the electron microscope to correct for optical aberrations. Finally, the projector lens system magnifies the image and projects it onto a camera.

AUTHORS' NOTE

Enzo Evers (Ph.D. candidate) and Tom Oomen (associate professor) are both associated with the Control Systems Technology group within the department of Mechanical Engineering at Eindhoven University of Technology in Eindhoven (NL). Ronald Lamers works as a thermal dynamic design engineer at Thermo Fisher in Eindhoven.
The authors gratefully acknowledge Niels van Tuijl for his contribution to this work.

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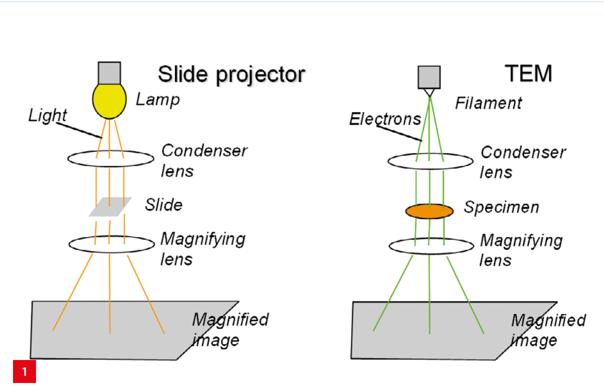
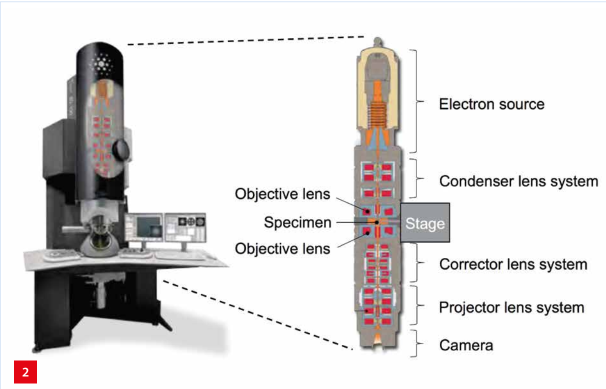


1 Similar operation principle of a slide projector and a transmission electron microscope (TEM) [1].



2 General overview of a transmission electron microscope [2].

Advanced Thermal Control Consortium

Thermo Fisher has joined the Advanced Thermal Control Consortium. The aim of this consortium is to advance the theoretical and applied approaches to design, simulation, measurement and compensation techniques essential for the development of precision modules/systems subject to internal or external thermal loads [3]. Within this consortium, a fruitful collaboration between Thermo Fisher and Eindhoven University of Technology has been set-up to expand the identification and control approaches available for thermal-mechanical systems.

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Because an electron microscope is capable of visualising objects at the atomic scale, it is a key enabler for nanotechnology, life science, material science and semiconductor technology. Electron microscopes are increasingly being used as analysis tools in laboratories and industry. Whereas the material science market is pushing the boundaries with respect to resolution of electron microscopes, markets as semiconductors and life science are pushing the boundaries with respect to throughput. In view of these increasing demands for throughput and resolution, the stability of electron microscopes becomes increasingly important.

Stability

Acquiring high-resolution images requires the exposure time of the camera to be sufficient long. The image acquisition process takes time, because a sufficient amount of electrons need to be detected in order to provide enough contrast in an image, which is the main measure for image quality. In fact, the contrast improves with increased exposure time. During the exposure time, the specimen must remain stationary with respect to the electron beam. Movement of the specimen, known as drift, would lead to a blurred image, as shown in Figure 3. In this context, stability is defined as minimal drift of the sample position with respect to the electron beam. At present, the state-of-the-art approach is to wait (minutes to hours) until the drift is low enough for high-quality imaging, which significantly reduces the throughput of the system.

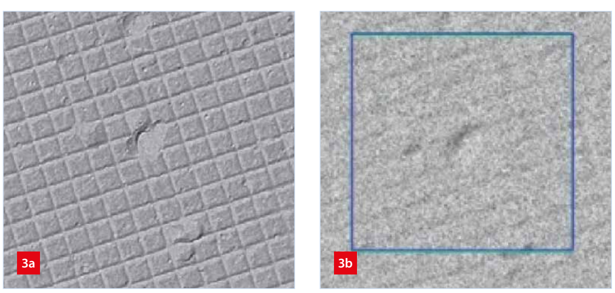


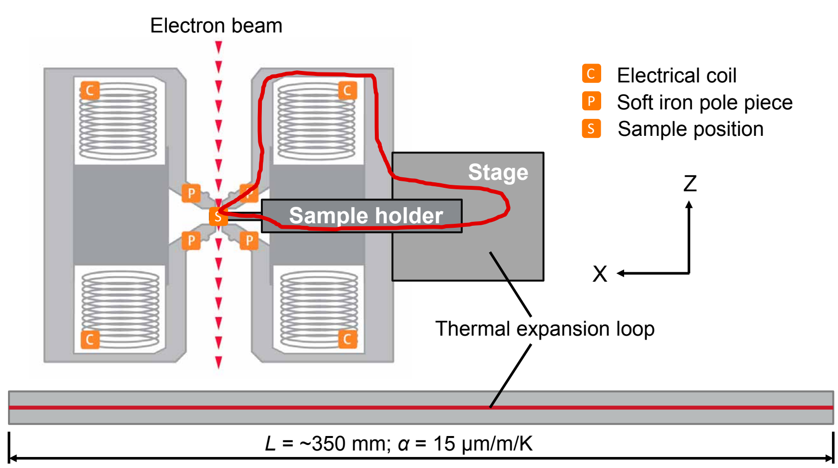
Image of an object (gold) [4].
(a) In high contrast.
(b) With blur.

For example, in life science applications a so-called single-particle analysis is performed to study single proteins that perform key roles in diseases in their native context in the cell at near atomic resolution. In such analyses, the microscope can be taking images automatically for several days, during which image quality, and thus stability (< 10 nm/min) of the electron microscope must be guaranteed.

Sensitivity

In Figure 4, a more detailed view is given on the specimen location inside the electron microscope. The specimen is placed on a sample holder, which will be positioned inside the sample manipulation stage and the electron microscope. Also shown in Figure 4 is the thermal expansion loop.

The thermal expansion loop covers parts of the electron microscope on which the stage has been mounted, parts of the stage, and parts of the sample holder. If the temperature of these parts changes due to thermal disturbances, they will deform, which will cause drift of the sample position with respect to the electron beam. The thermally induced deformation in X-direction is far more dominant than in Z- and Y-direction, therefore the thermal expansion loop can be considered as a sum of 1D expansions in X-direction of all parts inside the loop. The maximum allowed drift of the specimen is 0.5 nm/min.



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Main drift components and expansion loop.

For an impression of the required temperature stability, the thermal expansion loop is folded open; the total length is approximately 350 mm. If an average coefficient of thermal expansion is assumed for all the parts of 15 μm/m/K, the required temperature stability of the thermal expansion loop to meet the drift requirement of 0.5 nm/min is 0.1 mK/min. This temperature stability requirement is worst-case, since thermal expansions can cancel each other. However, the coefficients of thermal expansion and thermal time constants differ for all parts inside the expansion loop.

Main disturbances

The performance of electron microscopes is disturbed by mechanical vibrations and acoustics, and electromagnetic fields, but also due to thermal disturbances. These cause thermal-mechanical deformations of the system, which are observed in the image as drift. Thermal disturbances can be divided in external and internal disturbances. Main external disturbances are the air temperature variations in the electron microscope room and the temperature and flow variations of the cooling water. Main internal disturbances are temperature variations due to power dissipation variations of the electromagnetic lenses, motors and encoders.

A special case of disturbance is the insertion of a specimen holder. Typically, the temperature of the sample holder is not equal to that of the microscope. The sample holder has to take over the temperature of the microscope, and until a new thermal equilibrium is reached, the system will be subject to drift.

For counteracting acoustic disturbances high-end electron microscopes are placed in an acoustic enclosure, as shown in Figure 5. This acoustic enclosure also attenuates the effect of room temperature variations. The thermal time constant of such an enclosure is approximately 4 hours. This means that slow room air temperature variations, such as the day-night cycle, are still affecting the electron microscope, leading to thermally induced drift of the sample position with respect to the electron beam.

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Thermo Fisher Titan microscope outside an opened acoustic enclosure. (Photo: Leo Koomen)

Power dissipation inside the sample manipulation stage due to motors and encoders, albeit only a few milliwatts, causes drift. The power dissipation of the electromagnetic lenses is also a main thermal disturbance. Although most electromagnetic lenses are operated in a constant-power setting, this is not applicable for all lenses inside the electron microscope. So, the variation in the power dissipation of the electromagnetic lenses is also a source of drift.

System identification

To meet the ever-increasing demands to enhance the throughput and positioning accuracy, thermal deformations must be analysed and compensated for using real-time error compensation techniques and an appropriate thermo-mechanical model. Accurate modelling of precise thermo-mechanical systems is complex, e.g., due to uncertain parameters and contact resistances. Earlier solutions to compensate for the deformations in electron microscopes, for instance, cannot cope with large deformations and strongly depend on model quality [5] [6]. Therefore, an accurate parametric model is desired for a model-based approach. Ideally, using a limited amount of temperature measurements combined with an accurate thermo-mechanical model enables the deployment of error-compensation techniques [7] [8].

State-of-the-art at Thermo Fisher

The state-of-the-art for thermal-mechanical system identification within Thermo Fisher is to apply step-like heat load excitations, and measure the response in temperature and/or drift. In certain scenarios, e.g., for measuring cooling-water-related transfer functions, a square-wave waveform is used as input signal, with a duty cycle of 50%, in which the time period of the waveform is varying.

Models are tuned (as yet) manually based upon the measured data in the time and frequency domain. The time constants of the system can be as long as 12 hours. Especially long time constants often result in experiments, either in the time or frequency domain, running for multiple days. During these measurements, the experiment is influenced by disturbances, including the varying ambient temperature. These influences often lead to poor signal-to-noise ratios, so that the information obtained from the experiment is limited.