Title: Thermal design and time-dependent dimensional drift behaviour of sensors, materials and structures

Abstract

Industries, such as semiconductor manufacturing and aerospace, place ever increasing requirements for improved accuracies on high end production equipment and measurement equipment, however unwanted drift of material structures and sensors becomes a serious limitation on achievable system performance. There is a particular need for improved knowledge and control of medium to long-term dimensional drift properties resulting from intrinsic material and structural behaviour or environmental conditions. Traceable measurement of extremely small dimensional drift over long periods of time is one of the main metrological challenges of this SRT. Moreover, better temperature control and improved thermal design are necessary to limit adverse temperature effects on performance of such equipment. Appropriate temperature measurement and low vibration cooling elements are a prerequisite for successful temperature control. In order to optimise machine design knowledge of thermal material parameters such as thermal expansion, heat flow and the behaviour of connection methods like screwing or bonding must be enhanced. Improved knowledge combined with better design principles will benefit key European industries in terms of more efficient production processes including reduced downtime and more reliable, improved products.

Conformity with the Work Programme

This Call for JRPs conforms to the EMRP 2008, section on *"R&D for fundamental and applied metrology"* related to *Industry* on pages 12, 13, 35, 36, 38, 39 and 42.

Keywords

Precision engineering, high-end equipment, cost-efficiency, new materials, structural connections, dimensional metrology, dimensional stability, drift measurement, temperature measurement, control algorithms, CTE of materials and connection techniques, thermal modelling.

Background to the Metrological Challenges

Nearly all high precision measurement and production tools, ranging from machine tools to lithography equipment to high resolution microscopes but also mass balances and other instruments, are adversely influenced by thermal effects and by medium and long term dimensional drift which limit their performance. To meet the current trends in technological development, improvements in instrumentation accuracy are required, and ultimate stability in stable and controlled environmental conditions is of increasing importance. Instrumentation stability is directly linked to the recalibration interval, process control and system performance. Detailed knowledge on system drift on the medium to long time scale is required to assess and improve the uncertainty and to ensure efficient and economic use of the instrumentation and enable the production of reliable high quality products [1].

For example, the semiconductor industry is aiming for ever smaller integrated structures [2]. Lithography systems comprise complex lens assemblies and metrology systems, incorporating junctions such as bolts, kinematic contacts and adhesives and future lithography techniques such as EUV-litho, places even higher requirements on relative positioning of components and on their long-term stability. Lithography instrumentation in semiconductor industry is aiming to handle of ever larger wafers beyond 30 cm in diameter. The typical recalibration cycle for lithography instrumentation currently varies between several days and to weeks. Developments resulting in reduced drift or

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enhanced thermal design enabling the extension of the calibration intervals, would lead to reduced downtimes, extended production and reduced costs.

In the area of microscopy (for example electron microscopes) it is important that the images are stable during measurements. Users are increasing interested in studying processes under microscopes leading to longer measurement times. The influence of drift is therefore becoming more dominant and needs to be reduced and thermal design optimised.

The calibration standards for measuring instruments and machine tools also have to be very stable. New materials such as carbon fibre are now being used for as standards due to good thermal stability, however the long term dimensional drift is not yet well known.

Space instrumentation components and connections have to be stable over the lifetime (years) of the satellite [3]. Particularly tight dimensional uncertainty requirements and yet unknown properties of new materials, such as light-weighted SiC elements, occur in the space sciences and in the adaptive optical and interferometric elements of large terrestrial telescopes. For example the GAIA (Global Astrometric Interferometer for Astrophysics) required accuracies down to 50 pm, the more recent LISA (Laser Interferometer Space Antenna) has requirements are down to 2 pm level.

Fabry-Pérot displacement metrology has been demonstrated on laboratory level to 10 pm accuracy with sample extensions of 50 mm on a minute timescale [4], however long-term drift measurement in this regime has yet to be implemented. Commercially available displacement interferometry systems achieve accuracies at nm-level, mostly limited by the compensation for environmental circumstances such as air refractive index fluctuations and by instrument-dependent measurement nonlinearities.

Minimising deformations caused by temperature fluctuations and thermal gradients is a key problem for all ultra precision applications. Possible improvements include the minimisation of thermal distortions by more stable and homogenous temperature controlled measurement rooms and active cooling of heat sources. These methods are typically expensive and cause additional energy costs and maintenance effort but cannot be avoided in all cases. In implementing active temperature control, special care has to be taken regarding to ensure appropriate cooling elements, for example liquid cooling elements offer a good efficiency, but the coupling of vibrations from the liquid flow must be avoided by design. Sophisticated control algorithms therefore have to be implemented due to the high time constants of thermal effects.

One option to improve the thermal behaviour of mechanical systems is to minimise heat sources within the system by using energy efficient drives and sensors like position measurement systems. In addition appropriate design of the system can improve the thermal behaviour for example by using appropriate materials and intelligent placement of unavoidable heat sources. In the construction of the system not only the thermal expansion of materials but also their homogeneity and the thermal behaviour of joining techniques like screwing, gluing or soldering are important, critical is for example the mounting of sensor elements like CCD chips. Therefore design rules, better knowledge of material parameters, and efficient measurement and drive systems are required. Knowledge of the coefficient of thermal expansion is even more important for precision applications in space, where radiation from the sun can generate strong spatial and time dependent temperature variations. For an efficient thermal design the selection and optimisation of isolation materials or the material behaviour in the reflection and absorption of radiation also have to be taken into account, especially for vacuum or space applications in order to reduce the influence of the radiation. For a better understanding and optimisation of the designs, thermal modelling is a key component.

While new materials are increasingly used, there are open issues in the metrology framework for reference materials and the standardisation thereof. Sparse data is available on properties such as creep, hardness or coefficient of thermal expansion of new materials. The material parameters of many materials have been measured, but not even the coefficient of thermal expansion (CTE) at room temperature is known sufficiently accurately in some cases because many CTE measurements are only carried out over a large temperature range. Such needs have been identified by the CIPM WG on material property measurements and are underlined in the corresponding BIPM-VAMAS Memorandum [5, 6]. Furthermore, mandates for the development of indentation-based methods exists from the ISO/TC 164/SC2 and SC3 committees for ductility and hardness testing, respectively [7].

Scientific and Technological Objectives

Proposers should address the objectives stated below, which are based on the PRT submissions. Proposers may identify amendments to the objectives or choose to address a subset of them, in order to maximise the overall impact, or address budgetary or scientific / technical constraints, but the reasons for this should be clearly stated in the JRP protocol.

The overall objective is providing a sound metrological basis for quantitative medium/long-term dimensional drift behaviour and for improved thermal design in the development of (ultra) high-precision measurement and production equipment.

The specific objectives are:

1. Realising traceable measurements of dimensional drift (in the 10 to 100 pm uncertainty range, depending on time-scale) of materials, structures and sensors on a medium (minutes) and long (weeks) timescale and investigating effects of temperature, humidity and pressure on this drift. This includes:
    a. Establishing test facilities, techniques and procedures, ranging from one-dimensional measurements to multi-degree of freedom deformations for investigation of materials and structures.
    b. Investigation of intrinsic stability of the test facilities and high-end industrial equipment and the influence of environmental conditions. Next to the aim for excellent intrinsic stability, concepts will be investigated for a metrology platform insensitive to environmental fluctuations.
    c. Investigation of long term drift properties of various sensing concepts, such as optical displacement interferometry or capacitive sensing
    d. Study of temporal drift properties of materials and structures that are representative to the various industrial needs and establishing design rules for intrinsically stable high-end equipment.
2. Realising thermal optimisation and traceable thermal measurements for design of high-precision measurement and production equipment with minimal thermal sensitivity. This includes:
    a. Highly accurate and dynamic measurement of temperatures and temperature gradients (in the millikelvin range)
    b. Development of accurate, traceable, reliable measurement systems with long-term stability
    c. Investigation and measurement of thermal behaviour of materials, e.g. thermal expansion, homogeneity, thermal behaviour of joining techniques, insulation materials, etc
    d. Thermal modelling and optimisation of thermal design
    e. Establishing design rules for minimal thermal sensitivity

Proposers shall give priority to work that meets documented industrial needs and that which supports transfer into industry e.g. by cooperation and/or by standardisation.

Proposers should establish the current state of the art, and explain how their proposed project goes beyond this.

Potential Impact

Proposals must demonstrate adequate and appropriate participation/links with the “end user” community. This may be through the inclusion of unfunded JRP partners or collaborators, or by including links to industrial/policy advisory committees, standards committees or other bodies. Evidence of support from the “end user” community (eg letters of support) is encouraged.

Where a European Directive is referenced in the proposal, the relevant paragraphs of the Directive identifying the need for the project should be quoted and referenced. It is not sufficient to quote the entire Directive per se as the rationale for the metrology need. Proposals must also clearly link the identified need in the Directive with the expected outputs from the project.

You should also detail other impact of your proposed JRP as detailed in the document "Guidance for writing a JRP"

You should detail how your JRP results are going to:

- feed into the development of urgent standards through appropriate standards bodies
- transfer knowledge to the mechanical engineering, process engineering and production, communications and IT, automotive and aerospace, and other sectors.

You should also detail how your approach to realising the objectives will further the aim of the EMRP to develop a coherent approach at the European level in the field of metrology. Specifically the opportunities for:

- improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards
- the metrology capacity of Member States and countries associated with the Seventh Framework Programme whose metrology programmes are at an early stage of development to be increased
- outside researchers & research organisations other than NMIs and DIs to be involved in the work

Time-scale

The project should be of 3 years duration.

Additional information

The references were provided by PRT submitters; proposers should therefore establish the relevance of any references.

[1] "Roadmap Precisietechnologie", Innovation-driven research program (IOP) on precision technology, SenterNovem, www.senternovem.nl, Utrecht, The Netherlands, 22 January 2004.

[2] International Technology Roadmap for Semiconductors (ITRS), www.public.itrs.net.

[3] European Space Technology Platform Strategic Research Agenda V1.0 (2006) http://cordis.europa.eu/technology-platforms/pdf/estp.pdf, in particular section on Structures & Thermal Control, p. 74ff

[4] J. Lawall, "Fabry-Pérot metrology for displacements up to 50 mm", J.Opt.Soc.Am. A **22**(12), 2786 (2005).

[5] "Evolving Need for Metrology in Material Property Measurements", Report of the CIPM *ad hoc* Working Group on Materials Metrology (WGMM), BIPM, 2008.

[6] Memorandum of Understanding on Cooperation between the BIPM and the VAMAS, June 2008.

[7] ISO/TC 164 Business Plan "Mechanical Testing of Metals", 2004.