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Integration of Thermal and Dimensional Measurement – A Hybrid Computational and Physical Measurement Method

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Abstract. In dimensional metrology, often the largest source of uncertainty of measurement is thermal variation. Dimensional measurements are currently scaled linearly, using ambient temperature measurements and coefficients of thermal expansion, to ideal metrology conditions at 20˚C. This scaling is particularly difficult to implement with confidence in large volumes as the temperature is unlikely to be uniform, resulting in thermal gradients. A number of well-established computational methods are used in the design phase of product development for the prediction of thermal and gravitational effects, which could be used to a greater extent in metrology.

This paper outlines the theory of how physical measurements of dimension and temperature can be combined more comprehensively throughout the product lifecycle, from design through to the manufacturing phase. The Hybrid Metrology concept is also introduced: an approach to metrology, which promises to improve product and equipment integrity in future manufacturing environments. The Hybrid Metrology System combines various state of the art physical dimensional and temperature measurement techniques with established computational methods to better predict thermal and gravitational effects.

Keywords: Thermal variation modelling, Metrology, Light Controlled Factory

1. Introduction

Factories of the future have been the subject of much discussion and research in recent years. One such approach is the Light Controlled Factory [1], where optical metrology is traceably woven into the manufacturing process for increased product and equipment integrity.

Dimensional metrology is subject to thermal effects on measurement uncertainty in two main ways. The first is as the measurand will undergo thermal expansion, contraction and distortion. Secondly, measurements carried out using optical measurement-based technologies will be subject to refractive index variations associated with ambient temperature [2].

Even constant, uniform temperatures that are not 20˚C can be problematic, and it follows that transient ambient temperature modelling is even more challenging still [3, 4].

Two major points are made in the Guide to Uncertainty of Measurement (GUM) [5] that highlight the importance of working towards the integration of thermal and dimensional measurement:

- “7.1.3 Numerous measurements are made every day in industry and commerce without any explicit report of uncertainty.”
- “3.3.2 In practice, there are many possible sources of uncertainty in a measurement, including: … d) inadequate knowledge of the effects of environmental conditions on the measurement or imperfect measurement of environmental conditions”

The first point illustrates how uncertainty evaluation is often neglected, meaning that a number of measurements are recorded that do not give an indication of how close that measurement is likely to be to the True Value. Following this, it is stipulated that the instrument uncertainty can be inferred from the traceability of the calibration. The second point is particularly pertinent to this paper, as part of that uncertainty evaluation must include some characterisation of the environment in which the measurement is taken. In terms of uncertainty evaluation, this shows that relying on the calibrated instrument alone does not give a complete indication of the uncertainty of all measurements taken outside of the standard environment.

The same year as the last International Temperature Scale of 1990 was published, the literature on thermal effects was reviewed since 1967 and illustrated the extent of the challenges faced at that time [6]. Progress has been made in a number of areas, however much the same problems exist today.

Taking a hybrid computational and physical measurement-based approach offers the benefit of being able to quantitatively predict thermal and gravitational effects on products and equipment in non-standard metrology environments. This is of particular benefit to manufacturing in measurement assisted assembly (MAA) [7], which is increasingly applied in the aerospace industry [8].

2. Ambient Temperature Variation

Thermal gradients are often present at large volumes, with some indoor environments experiencing gradients of 3-5˚C. Over the course of the day, the temperature is likely to change by several degrees depending on the location. Temperature is considered to be one of the critical parameters in assembly processes, for example [9].

Significant effort and expense is involved in designing and characterising the performance of high specification metrology buildings, as was the case at Finland's Centre for Metrology and Accreditation (MIKES) [10]. Large volume enclosures have been created that exhibit ultra-high thermal stability of less than 1 mK [11].

For many companies, the business case for investment in closely controlling temperature is difficult to make, even for those involved in the manufacture of high value products. Rather than engaging thermal variation directly, it would be constructive for metrologists to instead accept measure temperature fluctuations and non-uniformities as they occur, using these measurements to make informed predictions about their effects. Even the most thermally stable environments will have some error, meaning that the same principle can be applied to go beyond what is currently possible.

3. Temperature Measurement

Initial research on the Light Controlled Factory identified key industrial temperature measurement technologies [12]. The scope of the review was to identify those technologies that were mature, commercially available and could operate over an extended range around room temperature (0-50˚C). A number of these sensor types could operate at much wider temperature ranges, which allows for the monitoring of various hot and cold processes that may be found in the assembly environment. These technologies will provide physical temperature measurement data to update thermal variation models, which can subsequently be used in thermal compensation.

Thermal expansion of different materials has been considered in relation to the uncertainty required for dimensional and temperature measurement. If the linear coefficient of thermal expansion is:

$$\alpha_L \Delta T = \frac{\Delta L}{L} \qquad (1)$$

Which can be used to provide the change in temperature ΔT representing the temperature measurement accuracy required:

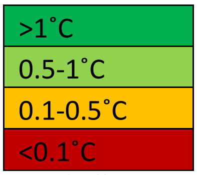
$$\Delta T = \frac{\Delta L}{\alpha_L L} \qquad (2)$$

Where α is the coefficient of thermal expansion (µm.m-1.˚C-1), ΔT is the change in temperature (˚C), ΔL is the change in length (µm) and L is the original length (m).

Values have been estimated for four commonly used materials:

- Aluminium 6061 [13]
- Titanium Alloy Ti6Al-4V [14]
- Structural Steel A36 [15]
- Invar [16]

These estimated values of ΔT have been assigned colours to indicate the accuracy of temperature measurement required with red indicating particularly challenging measurements and green being the least challenging as shown in Fig. 1.



🟩 >1˚C
🟩 0.5-1˚C
🟨 0.1-0.5˚C
🟥 <0.1˚C

Fig. 1. Colour coding of different levels of temperature measurement accuracy required

Table 1. Table of required temperature measurement for dimensional measurement scenarios of Aluminium 6061

CTE (μm.m^{-1}.°C^{-1})	L (m)	ΔL (μm)	ΔT (°C)
23.6	5	50	0.424
23.6	5	40	0.339
23.6	5	30	0.254
23.6	5	20	0.169
23.6	5	10	0.085
23.6	10	50	0.212
23.6	10	40	0.169
23.6	10	30	0.127
23.6	10	20	0.085
23.6	10	10	0.042
23.6	20	50	0.106
23.6	20	40	0.085
23.6	20	30	0.064
23.6	20	20	0.042
23.6	20	10	0.021

Table 2. Table of required temperature measurement for dimensional measurement scenarios of Structural Steel A36

CTE (μm.m^{-1}.°C^{-1})	L (m)	ΔL (μm)	ΔT (°C)
12.1	5	50	0.826
12.1	5	40	0.661
12.1	5	30	0.496
12.1	5	20	0.331
12.1	5	10	0.165
12.1	10	50	0.413
12.1	10	40	0.331
12.1	10	30	0.248
12.1	10	20	0.165
12.1	10	10	0.083
12.1	20	50	0.207
12.1	20	40	0.165
12.1	20	30	0.124
12.1	20	20	0.083
12.1	20	10	0.041

Table 3. Table of required temperature measurement for dimensional measurement scenarios of Titanium Alloy Ti6Al-4V

CTE (μm.m^{-1}.°C^{-1})	L (m)	ΔL (μm)	ΔT (°C)
8.3	5	50	1.205
8.3	5	40	0.964
8.3	5	30	0.723
8.3	5	20	0.482
8.3	5	10	0.241
8.3	10	50	0.602
8.3	10	40	0.482
8.3	10	30	0.361
8.3	10	20	0.241
8.3	10	10	0.120
8.3	20	50	0.301
8.3	20	40	0.241
8.3	20	30	0.181
8.3	20	20	0.120
8.3	20	10	0.060

Table 4. - Table of required temperature measurement for dimensional measurement scenarios of Invar 36

CTE (µm.m^{-1}.°C^{-1})	L (m)	ΔL (µm)	ΔT (°C)
1.3	5	50	7.692
1.3	5	40	6.154
1.3	5	30	4.615
1.3	5	20	3.077
1.3	5	10	1.538
1.3	10	50	3.846
1.3	10	40	3.077
1.3	10	30	2.308
1.3	10	20	1.538
1.3	10	10	0.769
1.3	20	50	1.923
1.3	20	40	1.538
1.3	20	30	1.154
1.3	20	20	0.769
1.3	20	10	0.385

As can be seen in Tables 1-4, the temperature measurement capability requirement becomes far more important for materials that are more susceptible to thermal expansion as would be expected. This generalized estimation is useful in the selection of temperature measurement technologies to be used in thermal variation modelling. It must be noted that these values are merely for estimation and in reality there will be some uncertainty in the coefficient of thermal expansion.

For more challenging measurement scenarios over long distances where low dimensional uncertainty is required, more invasive sensor types will need to be used. In most cases however, taking temperature measurements of the measurand and its environment will be preferable to solely monitoring temperature at the instrument.

4. Thermal Modelling and Computational Methods

A range of computational methods are available for metrology and modelling are used in industry. Simulation of thermal expansion, contraction and distortion is currently carried out at the product design stage, whereas this approach casts it in a more operational role.

The empirical modelling techniques can be employed if the thermal errors can be considered as a function of some critical discrete temperature points on the machine structure, and these temperature points need to represent the thermal field of the entire machine structure. For example, for machine tool thermal error modelling, a set of thermal sensors and a set of displacement sensors need to be placed at the appropriate locations of the structure in order to measure the temperatures and displacements. The coordinates and the temperature of the selected locations are initially measured as the reference. The data then records in a series of time periods during the warm-up and machine operations. A relationship between the thermal error and the temperature can be established based on these data using suitable algorithms, such as Multiple Regression Analysis (MRA), Genetic Algorithms (GA) or Artificial Neural Network (ANN) [17].

The effect of temperature upon the tolerance stack-up of assemblies is of great interest here. Various software packages can perform tolerance analysis on assemblies and methods for tolerance analysis have recently been the subject of a comparative review [18]. One 2013 study of assemblies in the automotive industry recommended that assembly variation simulations should be combined with thermal expansion simulation, rather than considered separately [19].

Composite materials are being used with increasing frequency in a number of industries, with the automotive and aerospace sectors being the most notable. Modelling composite materials can be difficult due to their relative non-uniformity and variation so this is an area that is being continually developed. The dimensional variation of composites has been simulated using FEA and studied for different types of simple structural assembly [20].

The prediction of the environmental change is required in large volume metrology in order to compensate measurement uncertainty and thermal-structural errors. Numerical Weather Prediction (NWP) [21] has the potential for use in ambient conditions prediction in large volume metrology applications Overall, there are several similarities: similar environmental conditions (such as temperature, humidity and pressure); both time dependent; both aim to predict the environmental change using the initial measurements. However, from a practical point of view, the challenge would be gathering large sets of real measurement and sufficient history data of ambient conditions of the real site to train the programme to achieve accurate predictions.

Modelling indoor ambient temperature has been studied for a number of applications, perhaps none more so than in Heating, Ventilation and Air Conditioning (HVAC). In addition to temperature, air flow has also been modelled within buildings [22]. As well as personal comfort (analogous here also to product and equipment integrity), the modelling of ambient temperature in HVAC applications is also important for the improvement of energy efficiency, with one building seeing 20% improvements [23]. This modelling has often been achieved through the use of thermal network analysis [24]. While HVAC may seem disconnected from manufacturing, the characterisation and prediction [25, 26] of room temperatures could be useful for daily dynamic thermal variation modelling.

5. Hybrid Physical and Computational Metrology Concept

Hybrid Metrology System is defined here as a system that utilises the measurement of more than one physical quantity to inform virtual computational models of the measurand within the context of its environment.

The Hybrid Metrology System is designed to be a modular system so that measurement and computational capabilities can be added or removed. In this case, dimensional and temperature measurement will be measured, although other measurements could also be taken as appropriate.

The overall anatomy of the Hybrid Metrology System consists of the physical and digital domains. The measurand and instruments occupy the physical domain within the inspection environment. Via the data acquisition and inspection software, measurement data can then be used within the digital domain to simulate thermal effects and predict their resulting impact upon dimensions and tolerance stack-up in assemblies. One example of a possible configuration of the Hybrid Metrology System can be seen in Fig. 2.

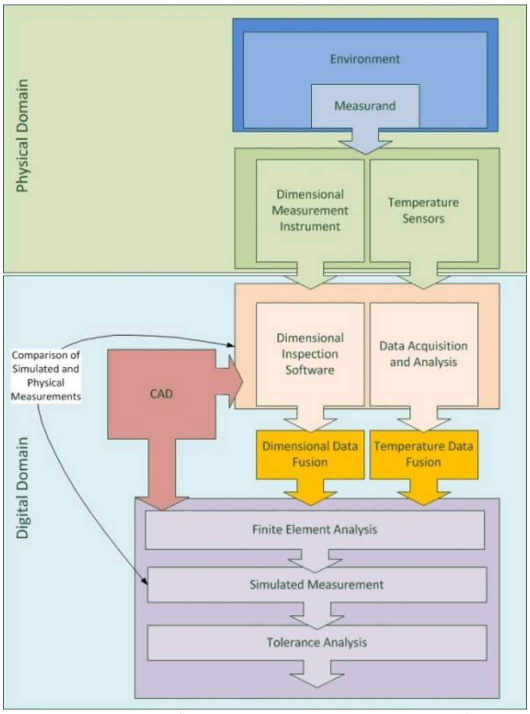


Fig. 2. One example of a Hybrid Metrology System configuration

In order to validate the model, deterministic simulation data must be compared against measurement data. Any discrepancies in the model predictions can be accounted for could be performed iteratively. Statistical analysis and machine learning methods offer efficient model development. Whilst running complex simulations is computationally expensive, cloud computing services may offer an advantage to the Light Controlled Factory. One possibility is cloud computing combined with part simplification algorithms to create dynamic virtual assembly process models. Processing in this manner could also be used to network several different sites in larger companies so that modelling improvements can be realised with Big Data techniques globally throughout organisations, rather than at individual sites. Fig. 3 illustrates levels of increasing developmental complexity for a Hybrid Metrology System.

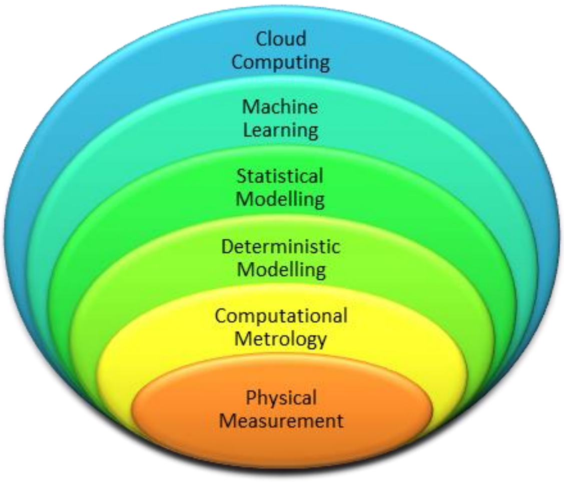


Fig. 3. Diagram showing levels of developmental complexity in Hybrid Metrology Systems

Uncertainty evaluation as discussed earlier is fundamental to the creation of a traceable metrology system of any kind. Uncertainty models are currently under development for a range of instruments that give uncertainty estimations for specific measurements taken. Due to the modular design of the Hybrid Metrology System, this can be incorporated as new uncertainty models are developed for each instrument. The uncertainty of the simulations themselves will also need to be evaluated.

Srinivasan created an integration framework for product lifecycle management (PLM) which supports information-sharing between the realms of engineering and wider business. This framework allows for the connection of separate software modules [27]. Monitoring the condition of equipment has been considered in the context of Product Lifecycle Management (PLM). It could be possible to include temperature measurement data and the Hybrid Metrology System as part of this framework [28].

6. Thermal Compensation

Using the predictions from the Hybrid Metrology Systems paves the way for improvement in manufacturing as thermal effects can be largely offset using thermal compensation.

Measurement and subsequent compensation of thermal effects has been the focus of various studies. This is particularly true for machining processes where the temperatures present are often beyond room temperature and the specifications of machined components are demanding - ultra precision machining for example requires sub-micron tolerances.

Machine tool errors attributable to thermal effects can be corrected in real time on machine tools [29].

In large scale assembly, the products are often high value and specifications are becoming increasingly challenging. This area has in recent years received a great deal of attention in order to improve assembly through increased measurement capability. As tooling is relied upon to hold assemblies, active thermal compensation has been identified as one potential solution to compensating for thermal expansion effects in large scale tooling for aerospace applications [30]. Often the parts of an assembly are compliant, where gravitational effects can also occur. The theoretical basis for a biomimetic system for dimensional error compensation in compliant assemblies has been outlined which could inform the Hybrid Metrology System approach applied in such cases [31].

FEA has also been employed for machine tool error prediction in last decade. FEA was used to simulate the effects of the major internal heat sources such as bearings, motors and belt drives of a small vertical milling machine (VMC) and the effects of ambient temperature pockets that build up during the machine operation [32]. The agreement with the experiment results range varies from 65%-90%. The offline simulation can also reduce the machine downtime.

7. Conclusion

The challenges faced in industrial dimensional metrology for manufacturing due to thermal and gravitation effects have been introduced and discussed. Whilst this is an area that has been researched for a number of years, thermal effects continue to contribute a great deal to measurement uncertainty and product quality.

A generalised developmental theory of hybrid computational and physical measurement has been outlined, with reference to some applicable lessons learned from earlier works in the field of thermal variation modelling in the literature. Research has been done in a number of specific areas and this particular approach seeks to create a wider framework to exploit these learnings in an industrial context, as part of the Light Controlled Factory. Suggestions have been made as to where hybrid metrology can fit within existing and novel Product Lifecycle Management (PLM) frameworks.

The Hybrid Metrology System concept has been discussed with some illustration of how a number of physical and computational metrological techniques can be used as part of a Hybrid Metrology System. The Hybrid Metrology System has been defined as a system that employs a number of physical quantities to inform computational models of the measurand within its local environment. An example Hybrid Metrology

System has been given to illustrate how the system could potentially be structured but the particular configuration will depend upon the final application. Thermal compensation techniques offer the ability to address thermal effects based upon predictions made by the Hybrid Metrology System. Ultimately, the Hybrid Metrology System is intended to have a practical, modular design that is traceable through uncertainty-consciousness.

8. Future Work

Following on from this theoretical basis and outline of the Hybrid Metrology System concept, future work is needed to look at the technologies that go to form the Hybrid Metrology Toolkit. Such a toolkit will provide a practical methodology and framework, which can serve as the basis for preliminary experimental studies in thermal variation modelling. Case studies need to be carried out in both laboratory-based and industrial environments in order to validate the methodology. Uncertainty evaluation of the modelling also needs to be carried out, which will require the modelling of uncertainty in physical dimensional and thermal metrology as well as evaluating the uncertainty of the computational models.

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