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Identification of Key Temperature Measurement Technologies for the Enhancement of Product and Equipment Integrity in the Light Controlled Factory

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Abstract

Thermal effects in uncontrolled factory environments are often the largest source of uncertainty in large volume dimensional metrology. As the standard temperature for metrology of 20˚C cannot be achieved practically or economically in many manufacturing facilities, the characterisation and modelling of temperature offers a solution for improving the uncertainty of dimensional measurement and quantifying thermal variability in large assemblies.

Technologies that currently exist for temperature measurement in the range of 0-50˚C have been presented alongside discussion of these temperature measurement technologies' usefulness for monitoring temperatures in a manufacturing context. Particular aspects of production where the technology could play a role are highlighted as well as practical considerations for deployment.

Contact sensors such as platinum resistance thermometers can produce accuracy closest to the desired accuracy given the most challenging measurement conditions calculated to be ~0.02˚C. Non-contact solutions would be most practical in the light controlled factory (LCF) and semi-invasive appear least useful but all technologies can play some role during the initial development of thermal variability models.

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Keywords: Thermal modelling; Light Controlled Factory (LCF); Temperature measurement

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1. Main text

In large volume metrology, thermal effects make a significant contribution to the uncertainty of measurements. Large structures that are often 20 m in length or greater are currently being assembled in factory environments where there can be thermal gradients of around 3-5˚C from floor to ceiling at any given time. Over a 24 hour cycle, the variation in ambient temperature can be as much as 15˚C.

Whilst dimensional measurements in industry are sometimes taken alongside ambient temperature measurements which are used for linear scaling within the metrology software, this is often a sole measurement at one point in space, at one instance.

One potential solution to the problem of thermally induced uncertainty is to model the thermal characteristics of the measurand. This can be achieved by monitoring the temperature and using this data to update a computational model that can more accurately predict the thermal and gravitational effects of the environment. The computational model makes use of the nominal CAD geometry of the measurand, alongside finite element analysis and tolerancing software.

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Modelling thermal effects has been studied in a number of applications, particularly in machining operations, ranging from estimation of machining characteristics in sink electro-discharge machining [1] to thermal modelling in chip-formation [2].

The Light Controlled Factory (LCF) is a futuristic vision where metrology permeates all levels of manufacturing in order to deliver improvements in product quality and increasing efficiency [3]. This follows on from previous work carried out where Muelaner identifies thermal variability modelling as one of the key enabling technologies in measurement assisted assembly (MAA) [4].

This paper aims to identify key technologies that would be suitable for temperature monitoring in a manufacturing environment that can be used alongside the computational model and will be geared towards this application rather than being a comprehensive review of temperature measurement.

Traceability of temperature measurement is important and a brief description of the International Temperature Scale of 1990 (ITS-90) is given. Calibration approaches are also simply described.

A number of commercially available technologies are outlined and have been split into different sections covering invasive, semi-invasive and non-invasive sensor types following the classification in Childs' review on the subject [5].

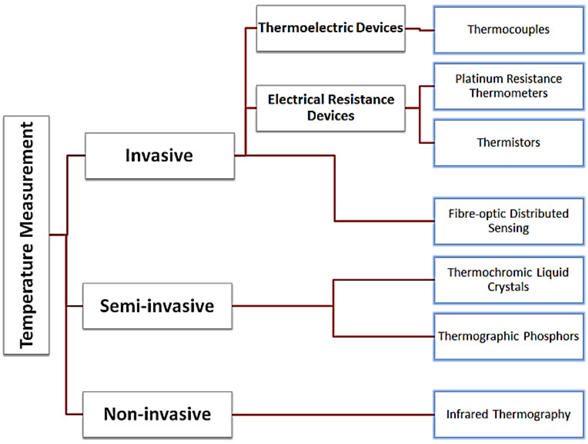

Fig.1 - Classification of key temperature measurement technologies adapted from Childs' review [4]

Practical considerations for taking temperature measurements generally are discussed, as well as envisaged measurement challenges in the factory environment.

2. Temperature Measurement Requirement for a Challenging Case

A calculation was carried out to estimate the accuracy required from the temperature measurement in relation to the dimensional uncertainty required. The most challenging case of 10 µm uncertainty over 20 m lengths was selected. Aluminium alloys are a common material in a number of industries and has a relatively large co-efficient of thermal expansion (CTE). 6061 aluminium is widely used and has a linear CTE of 23.6 $\mu m.m^{-1}.K^{-1}$ [6] which can be used to calculate an estimate of the required accuracy.

The coefficient of thermal expansion is given as:

$$\alpha_L \Delta T = \frac{\Delta L}{L} \tag{1}$$

Rearranging for ΔT gives:

$$\Delta T = \frac{\Delta L}{\alpha_L L} \tag{2}$$

Where α is the coefficient of thermal expansion ($\mu m.\ m^{-1}.K^{-1}$), ΔT is the change in temperature (K), ΔL is the change in length (µm) and L is the original length (m). The Kelvin is used in this particular calculation; 1 K is the same magnitude as 1 ˚C, despite being on a different scale.

Assuming the change in linear dimension to be the desired measurement uncertainty of 10 µm (best uncertainty case) over a length of 20 m (longest common distance) then the best required temperature measurement accuracy ΔT would be:

$$\Delta T = \frac{10\mu m}{20m \bullet 23.6\mu m m^{-1} K^{-1}} \tag{3}$$

$$\Delta T = 0.021°C$$

Although the above desired accuracy is given, this is an ideal goal given the most difficult conditions. Many temperature measurement systems will not be able to achieve this level of accuracy but this gives some idea of the challenges faced.

3. Possible Applications

3.1. Model Development

All of the measurement technologies can be used in initial laboratory-based experiments to develop and verify thermal variability models. It would be beneficial to trial a number of measurement systems as they can be compared against each other in terms of their data output and practicality. It is expected that the more accurate invasive temperature sensors will be used in the first instance and as the model matures, there will be less of an emphasis placed upon invasive systems in favour of more practical measurement from a distance that non-invasive types can offer, in line with the Light Controlled Factory vision.

3.2. Tooling Monitoring

Large assemblies require large jigs with a number of fixtures. This tooling is often monolithic and made of materials that are particularly susceptible to thermal effects in uncontrolled manufacturing environments. Monitoring the temperature of tooling is important as it will contribute significantly to product quality. Continuously measuring the temperature of tooling can be achieved using a number of technologies that have been highlighted with some technologies requiring more development in order to be incorporated into tooling.

Invasive temperature sensors can be built into jigs and fixtures, which would allow for more accurate measurement of temperature within tooling.

Semi-invasive temperature measurement generally comes in the form of a coating which can be applied to the surface that needs to be measured.

3.3. Product Monitoring

Continuous monitoring of the assembly itself will also help to improve the quality through the hybrid metrology approach but it could be argued that there are more practicalities that need to be considered than in the monitoring of tooling. Ultimately, the product needs to be manufactured and assembled to a high standard and using some measurement technologies, specifically more invasive ones, could affect the integrity of the product if not applied suitably. Whilst such difficulties could be overcome using more invasive sensor types, non-invasive sensor types are preferable in this case.

3.4. Integrated into Product

As sensor technologies become more sophisticated and decrease in scale as well as cost, more products now contain temperature sensors to provide their own internal health-checks. It could be possible to make use of such sensors beyond their normal working life, extending their use to include the assembly process. Embedded sensors would give a much more accurate picture of temperature distributions within an assembly and increase their cost-effectiveness by being allowed to contribute more widely.

3.5. Air Temperature

Ultimately, the majority of the thermal loading present on a structure will come from the ambient air temperature in the factory. Measurement of the ambient air temperature surrounding the assembly and tooling can be carried out using a number of types of temperature sensors and can be used in the computational model to allow more accurate boundary conditions to be specified.

4. Invasive Temperature Measurement

4.1. Thermocouples

Thermoelectric devices such as thermocouples are the most ubiquitous technique for measuring temperature and comprehensive standards are given for their use [7].

Thermocouples operate by exploiting the Seebeck Effect, in which two dissimilar conductors produce a difference in voltage when exposed to a temperature gradient along the wire, from the sensing tip to the end, according to the Seebeck co-efficient of the material. The electromotive force (emf) that is created through a temperature gradient is due to the diffusion of electrons in the material from the warm to cooler areas [8]. Because of this characteristic, a cold junction is sometimes necessary when the DUT temperature is close to that of the rest of the wire. Electronic cold junction compensation is also available.

Thermocouples are widely available and relatively low cost. Their outputs are quite low of the order of mV and so the accompanying electronics needs to be designed to boost the signal and attempt to reduce the possibility of any noise disturbance.

Accuracies between ±0.5˚C and ±2˚C can be realised using thermocouples over wide ranges, with accuracy suffering at very high temperatures although this range is outside of our interest. Over shorter ranges, pertinent to our near-ambient case, thermocouples can be calibrated to achieve accuracies closer to ±0.1˚C [5].

Perhaps the biggest source of uncertainty in thermocouples is the homogeneity of the wire. Since the thermocouple relies heavily on material properties, it is vital that the wire exhibits the same thermoelectric characteristics along its length. A number of studies have focused on inhomogeneity and methods for its evaluation [9-12] while some have focused on specific inhomogeneities and drift when using particular wire materials [11, 13-16], which is encouraging for the development of thermocouple capability.

Possible applications: Model development, embedded into tooling, air temperature; product monitoring.

4.2. Platinum Resistance Thermometers

For accuracy, standard platinum resistance thermometers (SPRT) are emphatically the devices of choice. SPRTs cannot be used in every situation: they are delicate and must operate in a controlled laboratory environment to perform correctly. SPRTs are capable of uncertainties of ±2 mK in good conditions [17].

The industrial counterpart to the SPRT, the industrial platinum resistance thermometers (IPRTs) are commercially available, lower cost and designed to be far more robust; they are able to withstand shock and vibration in uncontrolled factory environments. IPRTs can comfortably achieve accuracies of ±0.01˚C to ±0.2˚C [5].

Wire wound platinum RTDs are made by wrapping a length of platinum wire around a ceramic core and trimmed to meet the correct resistance: most common are the Pt100 type where the resistance is 100 Ω at 0˚C. The wire wrapped around the core is hermetically sealed inside a ceramic or glass capsule.

Thin film IPRTs consist of a thin film of platinum deposited onto a ceramic substrate. The platinum is trimmed to produce the correct resistance: Finally, the film and the substrate are encapsulated in an insulator much like other electronic components [18]. Recent development in thin film technology has enabled IPRTs to be mass produced relatively inexpensively.

IPRT sensors that can be mounted upon a surface or embedding within tooling may prove invaluable in the model development stage to achieve the accuracy required and integrated sensors within tooling could also be used in the manufacturing process.

Possible applications: Model development; embedded into tooling; air temperature; product monitoring.

4.3. Negative Temperature Coefficient Thermistors (NTCs)

Thermistors are another type of resistance temperature device that are semiconductor devices and their mode of operation is based primarily on resistance. Due to the properties of semiconductors, the relationship between resistance and temperature is non-linear [17].

The semiconductor materials can mean that decalibration and drift over time can be a real issue. With regular calibration and care, accuracies of ±0.01˚C can be achieved, although in industrial applications, this will often increase to as high as ±1˚C.

Thermistors generally find application in cases where accuracy is of lower importance and low cost sensors are required. NTCs are orders of magnitude more sensitive than PRTs and thermocouples [19]. Their sensitivity means that there is no longer any need for a four wire bridge circuit configuration and longer wires can be used if necessary. Another advantage of their sensitivity is the heat dissipation is considerably lower as power is inversely proportional to resistance. NTCs can be made to be relatively small, so can cause less of a disturbance to the measurand.

Possible applications: Model development; embedded into tooling; air temperature.

4.4. Fibre-optic Distributed Sensing (FDS)

Fibre-optic distributed sensing (FDS) uses the refractive index changes that occur when the fibre-optic is subjected to temperature or strain to provide measurements when calibrated.

There are several commercially available systems for sensing with a range of capabilities. Many of these systems can measure over tens of metres, with more specialised systems being available for distributed temperature measurement over hundreds of metres right up to several kilometres – the oil and gas industry has started to make use of this in pipeline monitoring [20]. The nature of this technology means that while the resolution and accuracy of temperatures can be good with systems capable of achieving 0.1˚C resolution and often less than a degree accuracy, their usefulness can be limited by their spatial resolution. The further the distance that is covered, the worse the resolution will get. Spatial resolutions are of the order of around 10 mm when using a fibre length of up to 70 m [21].

Networking of fibre optics has been of interest, which is something that would be useful for the Light Controlled Factory and a review of these studies was carried out in 2013 [22].

A secondary benefit of fibre optic sensing systems is that by using the same sensor, distributed strain measurements can be taken. Considering the loads that assemblies and tooling are subjected to during production, it could be beneficial for large volume thermal studies to make use of this technology.

Possible applications: Model development; embedded into tooling; integrated into product.

5. Semi-Invasive Temperature Measurement

5.1. Thermochromic Liquid Crystals (TLCs)

Liquid crystals can be used to measure temperature as their colour can change reversibly depending upon the temperature at the sensor. Often their appearance will alter from being completely transparent to showing a solid colour within the range of the sensor; above the range they again appear transparent. Often the TLC is mounted on a black background to allow for clearer temperature readings.

Whilst being liquid they also exhibit characteristics of crystals: when the temperature reaches a certain level, this causes the liquid crystals to go from an amorphous arrangement to a more crystalline state so that it reflects different wavelengths of light. These colours can be interpreted using a digital camera system linked to calibrated image processing software.

Typical accuracies for TLC indicators are modest with values of around ±2˚C but for many applications are counterbalanced by their low cost, ease of use and fast response times of around 0.5-2 seconds. TLCs in themselves do not require any power so there is no additional wiring necessary or self-heating effect present.

TLCs can be difficult to control due to their susceptibility to contaminants. As a result, they will often be encapsulated within a later of polymer in order to protect them from the environment [23]. UV light can also cause problems with TLCs. A number of commercially available TLCs have limited working lives due to these effects and will often be supplied with a use-by date.

Possible applications: Model development; applied to tooling.

5.2. Thermographic Phosphors

By exploiting the luminescent properties of phosphors, it is possible to determine surface temperatures. Thermographic phosphors are typically made from crystals doped with rare earth metals – ruby, and europium-doped Yttrium oxide are good examples that are commonly used [24].

In a number of cases, the method of coating is led by the ease of which it can be applied: sol-gel seems to be the method that requires less expensive equipment and is relatively simple. Brübach et al.'s 2013 review paper outlines a range of materials and methods of bonding them to surfaces [25].

Time resolved methods focus on the time taken for a certain intensity to be reached – either to rise, or to decay. Frequency domain phosphor thermometry relates to instances where the excitation used is continuous and periodic, rather than pulsed. Time-integrated methods focus on intensity, where one absolute intensity measurement can be taken or two, to give an intensity ratio [26]

Phosphor thermometry can be reasonably accurate, within 1% of the measured reading. This is also a technology that can operate over a relatively large range: from cryogenic temperatures up to beyond 1400 K.

Practicality is a major concern for phosphor thermometry and indeed TLCs that would limit their usefulness in large part manufacturing due to the coating requirement. They would be more suited to developmental work to characterise the thermal behaviour of large parts rather than integrated within an assembly process in most cases, although there is the possibility of such a thermometer being applied to large tooling structures.

Possible applications: Model development; applied to tooling.

6. Non-Invasive Temperature Measurement

6.1. Infrared (IR) Radiation Thermometry

Radiation thermometry is increasingly being adopted for use in industry in a wide range of applications. Radiation thermometers measure thermal radiation emitted from the surface of a material.

IR thermometers can measure the emitted thermal radiation within a small radius, dictated by the beam size and divergence of the laser so the measured radius is a function of distance from the measurand. Multiple probes could be useful in assembly processes as they could be mounted onto tooling such as jigs and fixtures to monitor temperatures of the assembly components non-invasively.

IR cameras can produce a thermal map of a structure or environment which is promising but are relatively expensive. They also have limited accuracy as the thermal radiation that is sensed by the camera isn't necessarily entirely emitted from the measurand.

IR cameras have been used in combination with computational models for machining applications. In one study, the temperature distribution during chip formation in the machining of a titanium alloy was estimated using a simplified model. Measurements from the IR camera were used to validate the predictions of the model [2].

Studies have shown it is possible to use IR cameras in a similar fashion to photogrammetry, where more than one camera can be set up at fixed positions to produce a three dimensional temperature map [27]. If integrated with dimensional metrology, this could be a useful tool for mapping temperatures in a factory environment.

IR line scanners are available to provide a temperature indication along a single line many times per second. Accuracies of line scanners tend not to be as good as fixed spot measurements due to the extra uncertainty involved in scanning. Typically accuracies of around ±3˚C are easily achievable with most of the systems currently on the market [28].

The advantage of being able to monitor temperature at a distance could outweigh the less accurate measurement that can be achieved using systems such as probes and line scanners. Provided the cost of IR cameras could be justified, this would also be a potentially powerful tool in factories of the future.

Possible applications: Model development; tooling monitoring; product monitoring.

7. Temperature Measurement Capability Comparison Table

Technology	Sensor Type	Accuracy (±˚C or %	Resolution (˚C)	Source	Possible Applications
Thermocouples	Invasive	0.1-0.5	0.01-0.1	[5]	Model development; embedded into tooling; air temperature; product monitoring
IPRTs	Invasive	0.01	0.001	[17]	Model development; embedded into tooling; air temperature; product monitoring
NTCs	Invasive	0.01	0.01	[19]	Model development; embedded into tooling; air temperature
FDS	Invasive	1	0.1	[21]	Model development; embedded into tooling; integrated into product
TLCs	Semi-invasive	0.1-2	1	[29]	Model development; applied to tooling
Thermographic Phosphors	Semi-invasive	1%	1	[25]	Model development; applied to tooling
IR Radiation Thermometry	Non-invasive	1-3	0.1	[5, 28]	Model development; tooling monitoring; product monitoring

8. Traceability

8.1. International Temperature Scale (ITS-90)

Temperature measurement standards are based on fixed temperature points where certain very predictable phenomena occur. The ITS-90 is a scale based upon the fixed point temperatures, from which national standard thermometers are calibrated [30].

The ITS-90 is still widely regarded as a good temperature scale that is unlikely to be updated in the very near future. Despite being a very useful scale, it is not without its imperfections: a few papers in the literature have studied the sub-range inconsistencies that are present within the ITS-90 that could be taken into account in the development of the next scale [31-33].

8.2. Calibration

Calibration can be carried out by comparing a sensor with the reading of an accurate sensor that has already been calibrated at a known temperature. PRTs are commonly used as the sensor against which others are compared.

In the calibration of radiation based thermometers, a blackbody source is held at a fixed temperature with a reference thermometer for comparison. Blackbody sources are either closely controlled furnaces or dry blocks. Where a furnace is used, thermocouples are often employed as the reference thermometer due to their high temperature capability.

It is important to ensure that sufficient time is allowed for the reference and sensor to be calibrated to fully stabilise before readings are taken.

In the Light Controlled Factory scenario, setting up an in-house measurement verification and calibration facility for all metrology systems would be advantageous.

9. Practical Measurement Considerations for Sensor Deployment

9.1. Thermal Contact

To accurately measure the temperature of a solid the sensor has to be matched as closely to the temperature of the measurand as possible – a temperature sensor will only ever observe its own temperature. Where the situation allows, mounting the sensor inside a hole will often give the best results as thermal contact will improve whilst the influence of ambient airflow will be negated.

Often drilling holes in the measurand is not an option and a surface temperature measurement will need to be made. Again, the sensor has to make good thermal contact with the measurand which can be achieved through mounting the sensor inside a small aluminium block adhered to the surface, for example. The airflow around the temperature sensor will affect the measured temperature making surface measurement more difficult still.

9.2. Emissivity

One of the difficulties in taking measurements using infrared-based sensors is that for any given surface, the emissivity value will be different.

Emissivity is a dimensionless quantity that represents the ratio of the amount of energy radiated by the surface of interest to that of a black body at the same exact temperature. Black bodies with an emissivity of 1 are those that are all-absorbing: they radiate no thermal radiation at all.. A surface exhibiting zero emissivity would be one that radiates almost all of the energy from the surface.

The main variables affecting the emissivity of a surface are: material, temperature, surface roughness, wavelength and angle of observation.

Extensive tables of common materials' emissivities are widely available but these should be treated as guides. Industrial applications make the value for emissivity more difficult to interpret, as any surface contaminants present would change the emissivity.

Recent studies have focused on finding methods to measure emissivity and also quantify uncertainty due to emissivity infra-red temperature measurements which will further aid the development of radiation thermometry [34, 35]. Another interesting avenue is work that has been carried out by Herve et al. is in the development of simultaneous temperature and emissivity measurement [36].

9.3. Environment

Carrying out accurate temperature measurements requires some consideration of the environment in which the measurements are carried out. The most important factor that has been mentioned already is the approximate temperature of the measurand and whether the sensor can operate at this range.

Magnetic fields and other electrical equipment used in the vicinity also have to be taken into consideration. This would be something to consider during sensor selection but is also very important for the data acquisition system used as this can cause interference.

9.4. Data Acquisition

Having the ability to log data automatically over protracted periods of time is essential for the inception of the Light Controlled Factory.

Hardware and software to enable data logging is generally compatible with a large number of digital thermometers that are currently on the market. Thermocouples, as thermoelectric sensors and one of the most widely used temperature measurement devices have a great deal of accompanying devices to enable data logging.

Demand for wireless connectivity is rising as the technology becomes more widespread. A number of temperature sensor manufacturers currently produce wireless sensors that can connect to dataloggers from a distance.

9.5. Sensor Positioning and Data Fusion

The number and positioning of sensors is very much an experimental process. Often if there is a particularly critical area or a complex thermal profile, the density of sensors will need to be higher. To reduce cost, time and thermal disturbance it is preferable to use as few sensors as possible whilst still getting the information that is required from the measurand.

At the large volume scale there does not appear to be a great deal in the literature about sensor positioning and density optimization, which would be useful to explore in more depth. Such studies have been carried out on smaller scale applications however using a variety of approaches [37, 38].

On a far larger scale, work has been carried out on temperature sensor positioning in areas such as meteorology, oceanography and geology – sometimes under the guise of spatial sampling design. One study takes a Bayesian approach to optimising the distribution of 50 sensors placed around the UK to measure air temperature [39].

Strides made in sensor positioning on a large volume metrology scale would be beneficial for creating measurement strategies tailored for specific product and process needs more simply whilst minimizing setup time.

Research has been carried out in the area of combining several sensors; one notable example being a 1992 paper which looked at synthesising information from multiple sensors resulting in improved accuracy, reliability and a reduction in random noise from sensors [40]. The areas of sensor and data fusion need to be explored in greater depth in future work.

9.6. Air Temperature

When measuring the air temperature present in a room it is important to consider where best to place a sensor to give the most accurate reading. The temperature is likely to be different depending on where in the room the temperature is measured. In uncontrolled environments it would be useful to take air temperature readings at a number of points around the room. Similarly, in uncontrolled environments there is likely to be a temperature cycling effect over time so taking periodic measurements over the course of a day will be required.

10. Future Work

Sensor positioning and density optimisation as well as data fusion of temperature sensor networks need to be studied in greater detail. Developing the finite element model and combining this with physical measurement is also a research priority. Validation and verification of the model can later be carried out and tolerance analysis can be added to the model to produce a full hybrid metrology system.

11. Summary

Key state of the art temperature measurement systems for near-ambient temperatures have been identified with some of the capabilities and typical specifications of particular measurement devices given.

Technologies that stand out in particular are those that are already commonly used in industry: thermocouples and platinum resistance thermometers. In terms of accuracy, PRTs can achieve excellent results, while NTCs are the most sensitive. Thermocouples on the other hand are widely available, provide reasonably good accuracy and are relatively low cost.

Non-invasive technologies may be less accurate, particularly within ambient temperature scale ranges but their practicality and ability to take large areas of data is undeniable.

Semi-invasive technologies appear to be limited in their usefulness. They are less accurate than their more invasive counterparts and more difficult to implement than non-invasive instruments but would provide a low cost solution for thermal imaging in some areas.

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