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Quantitative Thermal Imaging

Condition monitoring and healthcare diagnostics

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Quantitative thermal imaging, the measurement of temperature by use of thermal imaging devices, is reviewed here from a metrological perspective with a focus on measurement confidence and system application to fields such as condition monitoring and healthcare diagnostics. Thermal imaging has seen greatly increased application for the measurement of temperature following dramatic improvements in practicality and price. Selected thermal imaging systems are reviewed here by providing some example measurements outputs from devices, highlighting their outcomes on measurement confidence and impact on practical use, such as in condition monitoring and healthcare diagnostics.

1. Introduction

Temperature is a pervasive measurement parameter, used regularly and extensively in society. It is served well by long established practical measurement foundations (namely the International Temperature Scale of 1990 (ITS-90) (1)) and measurement tools such as: contact temperature probes (thermocouples, thermistors, platinum resistance thermometers and liquid in glass thermometers) and non-contact temperature probes (single spot infrared radiation thermometers). The measurement foundations and tools for these established thermometry technologies have several decades of practical use, end user experience, knowledge and associated measurement foundations (test, calibration and standardisation) summarised in (2). Thermal imaging has a large (and growing) number of system providers but by comparison to existing measurement tools a comparatively brief history of practical temperature measurement, a limited breadth of end user knowledge and sparse measurement foundations (3).

Thermal imaging systems have a broad range of end uses ranging from 'inspection' systems where qualitative only outputs are required to diagnostic devices (for example, COVID-19 temperature fever screening devices) where quantitative capabilities are a necessity. Increasingly, due to the provision of a temperature output, users are exploiting the benefits of thermal imaging systems for temperature measurement. However, not all systems are suitable for such use without additional measurement assessment (for example, calibration, metrological assessment) and moreover the practical measurement foundations, system knowledge and end user experience still remain comparatively speaking in their infancy.

The first factor we explore here is that of temperature measurement traceability to international standards. The current internationally agreed temperature scale is the ITS-90 (1). This is maintained and disseminated by metrology institutes (such as National Physical Laboratory (NPL) in the UK, or National Institute of Standards and Technology (NIST) in the USA). Demonstrable traceability to ITS-90 is necessary to ensure that one is measuring an internationally agreed temperature. Accreditation to ISO/IEC 17025:2017 (4) helps to provide independent confirmation that the calibration of devices (providing demonstrable traceability) is completed in a robust and rigorous manner. Such measures are commonplace in the established temperature sensing market, for example, single spot infrared radiation thermometers, thermocouples or platinum resistance thermometers (2). Here we present measurement data that assesses the temperature output of commercially available thermal imaging systems *vs*. ITS-90. We then look at the outcome of these measured outputs and discuss their impact on end-use application.

The second factor we explore here is one example of a user adjustable or system pre-set parameter, specifically in this case a flat field correction (FFC) interval. The FFC is used in thermal imaging systems to correct for sensor drift, typically when a FFC command is issued an internal shutter will pass in front of the detector to provide a uniform, known temperature scene filling the field of view of the detector. The FFC will be at factory set to do this automatically for either a specific temperature drift for example, 1°C shift in camera temperature, or after a specific time period for example, 5 min since previous FFC. The FFC event itself can also be adjustable for example, length of exposure or number of frames to average.

There are in fact a broad range of pre-set, automatic or user definable parameters that are used in order to provide the user with a visually high quality image and to maintain operability across a broad range of scene conditions such as: gain, dynamic range, flat field correction rates or non-uniformity correction modes (5). Each of these parameters can impact on a system's capacity for reliably providing temperature measurement data.

In this paper we present measurement data that assesses the temperature output of commercially available thermal imaging systems *vs*. ITS-90 for a range of different parameter settings of FFC. We then look at the outcome of these measured outputs and discuss their impact on end-use application.

2. Results and Discussion

2.1 Measurement Traceability

Commercial off-the-shelf thermal imaging devices were assessed using NPL's precision blackbody reference sources, providing fully traceable radiance temperatures, for a range of set point temperatures across the working range of the devices under test (DUT). For each set point temperature the DUT was aligned so as to be viewing centrally and directly down the blackbody reference source (30 mm diameter aperture) and at a working distance (lens to aperture) of nominally 1 m. For each set point temperature a series of displayed thermal imager temperatures from a fixed region of interest (ROI) (15 mm diameter circle) of the DUT was recorded simultanesously (average indicated temperature over ROI) with the blackbody reference source temperature (ITS-90). A set of recorded measurement data from two devices is shown in **Figure 1**. This measurement data shows the agreement between device displayed temperature and ITS-90 temperature varies with respect to source temperature. The disagreement between the two highlights the impact of poor measurement traceability and calibration. A detailed reporting of such data is available (6).

Temperature data output can be employed for a specific application such as that described in (7) for surface temperature measurement for condition monitoring. The outcome of these measured offsets are that both Imager A and Imager B will exhibit a systematic offset in temperature. Looking at the potential impacts for a condition monitoring example: for an artefact temperature of nominally 150°C Imager A would under read the apparent surface temperature by nominally 1°C whereas Imager B would under read the apparent surface temperature by nominally 5°C. The potential impact of Imager B's systematic measurement offset could result in a potentially critical error in either trend analysis or diagnostic threshold condition setting.

2.2 System Parameters

A commercial off-the-shelf thermal imaging system was assessed against an NPL precision blackbody temperature reference source held at a fixed temperature. The measurement output of the DUT was recorded for a range of user adjustable FFC parameters. The displayed thermal imager temperature was recorded and compared to the ITS-90 recorded temperature (baseline, **Figure 2**) for three different FFC settings: a 30 s, 60 s and 120 s interval between FFC events. The recorded measurement data and a baseline for the thermal imager under test are shown in **Figure 2**.

The measurements presented in **Figure 2** provide an indication of: (a) the apparent temperature measurement outcomes when varying a user

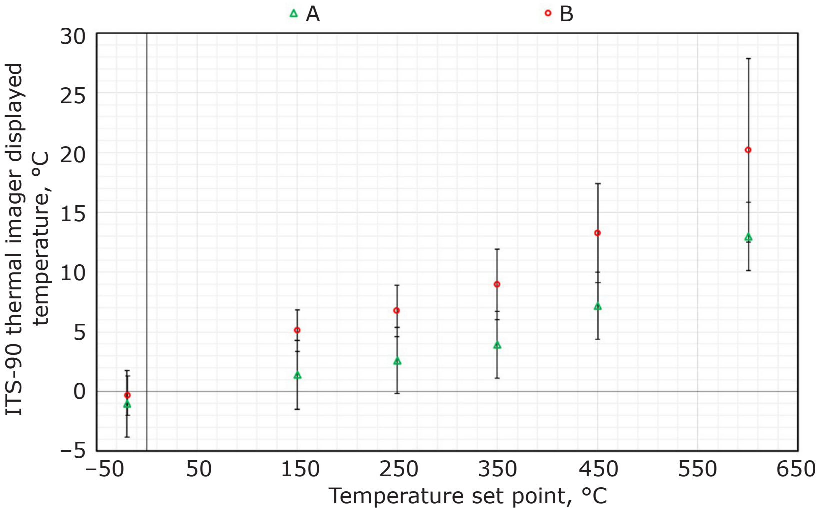

Fig. 1. A plot of the difference between ITS-90 temperature and displayed thermal imager temperature, when viewing a precision blackbody reference source, for a range of set point temperatures. Measurement data for two commercially available thermal imagers, denoted as Imager A and Imager B. The temperature measurement data from the thermal imagers is the average measured within a region of interest 15 mm in diameter, with a blackbody aperture of 30 mm, taken at a distance of nominally 1 m

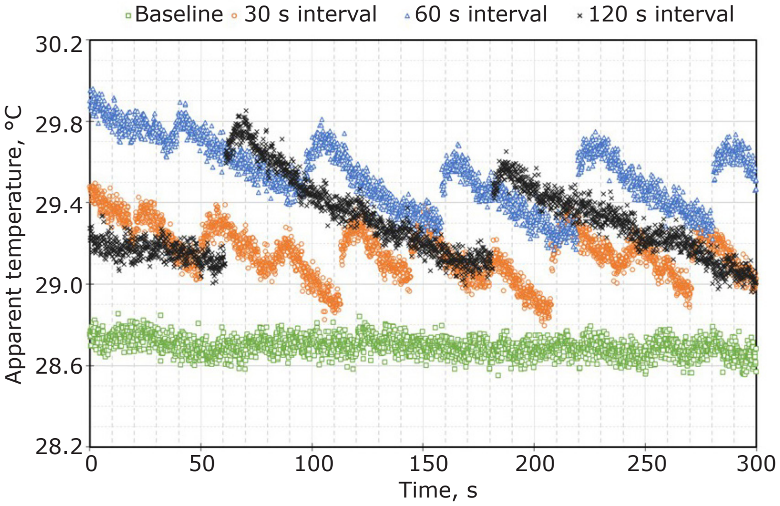

Fig. 2. A plot of the recorded thermal imager apparent temperature *vs*. time for different FFC interval periods: 30 s, 60 s and 120 s showing the variation in displayed thermal imager apparent temperature *vs*. reference blackbody source ITS-90 temperature (baseline)

adjustable setting (the FFC interval period) on a thermal imager; and (b) the peturbation of apparent thermal image temperature during FFC events. The DUT data shows: a nominal full range (span) of ±0.6°C for the FFC intervals tested, measurement instability post FFC event and an offset from baseline (ITS-90) temperature. Such temporal instability in use cases such as that of medical thermography (8) would significantly impact the diagnostic capacity of the system so as to require careful understanding and selection of FFC parameters.

3. Conclusion

Temperature measurement is a pervasive measurement parameter. Established and existing measurement tools are, broadly speaking, well understood and well served by the established measurement foundations, user knowledge and experienced temperature measurement instrumentation providers. Thermal imaging, comparatively speaking, is broadly speaking a qualitative tool. Its increasing use as a temperature measurement tool should be balanced by increased research into measurement foundations, user knowledge and experience in temperature measurement instrument providers. Few have rigorous traceability to ITS-90 (**Figure 1**) and have pre-set or user adjustable parameters that significantly impact the devices capacity for temperature measurement (**Figure 2**). While the underlying status is challenging for off-the-shelf temperature measurement, where these issues have been managed by reliable measurement foundations these devices have been shown capable of providing a constructive role in many sectors such as condition monitoring (7) and healthcare (8). Conversely if these parameters have not been fully accounted for in the management of the thermal imaging system the user is open to significant uncertainty and doubt in measurement. In scenarios such as critical or diagnostic healthcare applications significant effort is required in order to satisfy the need for high confidence in these measurement systems.

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Graham Machin is a Senior NPL Fellow in Thermometry. His team made world-leading contributions to the redefinition of the kelvin (K), thermodynamic temperature measurement and the development of high temperature fixed points as next-generation temperature standards. In addition, his team have made numerous contributions to solving thermometry problems in harsh environments as diverse as aerospace, space, nuclear decommissioning and medical, and is working towards developing traceable surface thermometry, *in situ* validation and no-drift sensing thermometry techniques to facilitate autonomous production (Industry 4.0). Graham is also the NPL science lead for nuclear decommissioning metrology.

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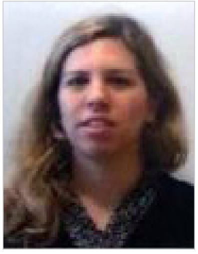

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