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Thermal compensation of photogrammetric dimensional measurements in non-standard anisothermal environments

David Ross-Pinnock*, Glen Mullineux

University of Bath, Claverton Down, Bath, BA2 7AY, United Kingdom

* Corresponding author. Tel.: +44 1225-386-052 ; *E-mail address:* d.r.ross-pinnock@bath.ac.uk

Abstract

Manufacturers are currently facing large volume metrology challenges driven by thermal effects such as variation in refractive index and thermal expansion. Thermal expansion is one of the largest contributors to measurement uncertainty and it can often be difficult to realise the standard 20°C temperature required. The current process for dimensional measurement requires that the temperature is measured at the instrument, and the entire measurement volume is scaled linearly by the same factor. Unfortunately, this assumes that temperatures are uniform all over the measurand, which is seldom the case particularly at large volume scales.

Useful for deformation measurement, photogrammetry is increasingly employed in industry, which in some cases can exhibit uncertainties comparable with the industry standard laser tracker. By measuring temperature more broadly and combining this data with finite element analysis, it is possible to compensate each of these points in 3D space along the X, Y and Z axes. Actively creating challenging metrology conditions with highly localized temperature gradients, and maximum temperatures in excess of 45°C has allowed this approach to be tested. Results show that in many cases it is possible to make localized predictions of displacement within the range of photogrammetric measurement uncertainty.

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Keywords: Thermal compensation; large volume metrology; photogrammetry; finite element analysis; Light Controlled Factory

1. Introduction

Manufacturing products with increasingly challenging specifications requires dimensional metrology that is capable of providing accurate measurement. One of the largest contributors to measurement uncertainty is thermal effects [1, 2], either due to refractive index variations in air in the case of optical metrology, or more generally, through thermal expansion. This being known, the standard temperature for metrology was defined as 20°C [3]. Temperature-controlled metrology labs are available, however temperature control is not always possible in industry. Particularly at the large volume scale, where products are being assembled over tens of metres, closely controlling temperature to 20°C is often economically prohibitive or impractical.

Currently, the most common means of solving the problem of metrology at non-standard temperatures is to measure the ambient temperature and scale the entire measurand linearly based upon the co-efficient of thermal expansion for the material. This assumes that the temperature distribution upon the measurand is uniform, which is seldom the case. Temperature gradients have been observed in large volume assembly, integration and test (AIT) environments of 3-5°C. Considering a commonly used aerospace material is aluminium, with a relatively large thermal expansion of around 23 $\mu m \cdot m^{-1} \cdot °C^{-1}$, measurement uncertainty due to

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thermal expansion will accumulate quickly at this scale. Assembly variation is also increased due to this expansion.

A novel method has been created to compensate dimensional measurement for anisothermal non-uniform thermal expansion at non-standard temperatures. This hybrid computational and physical measurement-based approach combines metrology instrumentation with simulation to more accurately predict thermal expansion. Temperature measurement technologies have been identified for use in assembly environments [4] and the body of literature on recent developments pertaining to these technologies has been reviewed [5]. The methodology behind this approach has been outlined [6], which laid the framework for this technique, which is studied experimentally here.

2. Measurement Scenarios

2.1. Frame structure

A cuboidal frame structure made from aluminium 6063 extruded profile by MiniTec is to serve as the measured object in this study. The frame is made up of 12 individual beam members and fastened together with proprietary MiniTec Powerlock fasteners. Supporting the frame at the bottom are 4 Omnitrack ball transfer units. Four plates adhered to the floor give the ball transfer units a low friction flat surface to run on, allowing for largely unimpeded thermal expansion in three directions. One ball transfer unit is nested in a hole drilled on one of the plates in order to provide constraint. A fiducial post is also used to reset the frame against repeatably, and to constrain yaw rotation of the structure.

2.2. Heating method

The ambient temperature of the environment is typically the source of thermal inhomogeneity in industrial assembly environments, meaning that using a convective heating method in the form of a fan heater would be considered a realistic, but exaggerated heating method for this experiment. Two heater settings have been used on a fan heater, and directed toward the frame structure in one corner. This localized heating provides an extreme example which will produce a significant amount of thermal expansion. At this scale in these conditions, the measurement uncertainty of the photogrammetry is of the order of 20 μm, whilst the thermal expansion is likely to be around 200 μm from initial measurements. This order of magnitude difference between measurement uncertainty and thermal expansion will allow variation due to thermal expansion and variation due to measurement uncertainty to be largely separated.

2.3. Design of experiments

Measurements are taken at ambient temperature (H0) before each round of heating to get a set of reference co-ordinates to apply compensation. This should also mitigate any hysteresis effects upon the structure. For each scenario, a single finite element model was used with the measured temperature data from both of the measurement scenarios and applied as boundary conditions. The first measurement is carried out at heater setting 2, position 1 (H2P1) and the second is carried out at heater setting 1, position 2 (H1P2). Agreement between the measured data and the simulated measurement data is the performance metric for this experiment.

3. Metrology

3.1. Dimensional metrology (photogrammetry)

Photogrammetry is a dimensional measurement technique that is increasingly used in industry to measure deformation, often in the automotive and aerospace industries. Targets are adhered to the surface of the measurand alongside reference objects such as scale bars and reference crosses. Scale bars provide a calibrated distance measurement between two points and reference crosses set the origin and orientation of the co-ordinate system. Multiple photographs are taken of the scene and Software is used to perform the bundle adjustment between each of the images and turns the measured targets into 3D co-ordinates by finding the centre of an ellipse present in the images. Images are captured exclusively in greyscale and targets are black and white to provide reproducible contrast. Software also uses RGB colour values to recognise these. Coded targets can also be used which have specific patterns that are recognised by the software to represent a point.

The Aicon DPA system used here is formed of a modified Nikon 3dx digital single lens reflex (DSLR) camera equipped with a 28 mm Nikkor prime lens. A hot-shoe-mounted flash with built-in diffuser illuminates the scene. Captured images are sent directly to a laptop computer via local Wi-Fi connection. Aicon 3D Studio software running on the laptop is used to perform the measurement and is also used for analysis of measurement data.

The Aicon DPA system was used to take measurements of the frame in each of the scenarios. With free-roaming handheld photogrammetry, a lot of the measurement capability comes from the images being captured from a wide range of angles and elevations. Fig. 1. shows the various

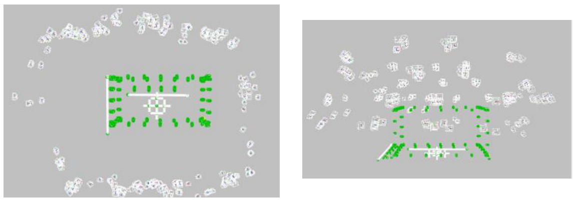

Fig. 1. Example image illustrating variety of vantage points used during photogrammetric measurement from the a) top view and b) side view

camera positions that were used during measurement. At each position, images are captured in portrait and landscape. Around ten vantage points were used with the photographer stood on the floor, from which photographs were taken at both standing and crouching positions. The frame stands at little