

Chapter 21

Experimental Analysis of the Thermo-Elastic Behaviour of Machine Tools by Means of Selective Thermography and Close-Range Photogrammetry

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Abstract The measuring methodology developed in subproject C06 provides an efficient analysis of the thermal and thermo-elastic behaviour of machine tools. Contactless measurement of deformations and displacements by means of close-range photogrammetry, as well as temperature measurement using selective thermography make possible high structural resolution with minimal instrumentation and measurement execution effort. In conjunction with distributed data logging, Data acquired inside and outside the control are considered and provide information for a comprehensive database for analysis.

21.1 Introduction

As a rule, temperatures and displacements can only be measured on the surface of structural components. Heat flows can be calculated from kinematic and load parameters by means of power dissipation approaches, assuming known parameter dependencies. Temperatures are mostly acquired in a tactile way on the surface of parts and subassemblies, requiring great effort to fasten, calibrate and wire the temperature sensors. Tactile displacement and deformation measurements demand,

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as described in Weck (2006), an expensive temperature-stable measuring platform (e.g. a rod framework made of Invar steel). The great instrumentation effort needed for the measurements, as a rule, results in a compromise in the benefit of low structural resolution—in other words, a small number of measuring points. The application of the thermography measurement technique to determine temperatures and temperature fields and the optical measuring method to quantify deformations and displacements offers a method to achieve higher structural resolution. Using the contactless measuring methods of both close-range photogrammetry (Fig. 21.1, left) and selective thermography (Fig. 21.1, middle), it is also possible to significantly reduce the instrumentation effort. In close-range photogrammetry, deformations and displacements are acquired at predefined measuring points on the part's surface. In case of subproject C06 the measuring points are defined by photogrammetry-targets. Selective thermography utilises the information in the visible (optical) range of the spectrum and projects the coordinates of the targets onto the thermal image, thereby making use of the known relative orientation of the optical and thermographic cameras. Temperature is measured in a selective manner at the targets. The targets exhibit a high degree of emissions, which, in turn, enhances the accuracy of the temperature measurement, particularly for shiny metallic surfaces.

Up to now, data available in the machine control, such as revolutions per minute and feed rates, have only been considered to a minimal extent or not at all during the analysis along the thermo-elastic functional chain. But these are useful input data, for instance, for power dissipation models. The database for machine analysis can be significantly expanded by the synchronised acquisition of control-internal and -external measured data by means of distributed data logging (Fig. 21.1, right). Consequently, in the subproject, a software framework was engineered for distributed data logging to be applied to various control systems.

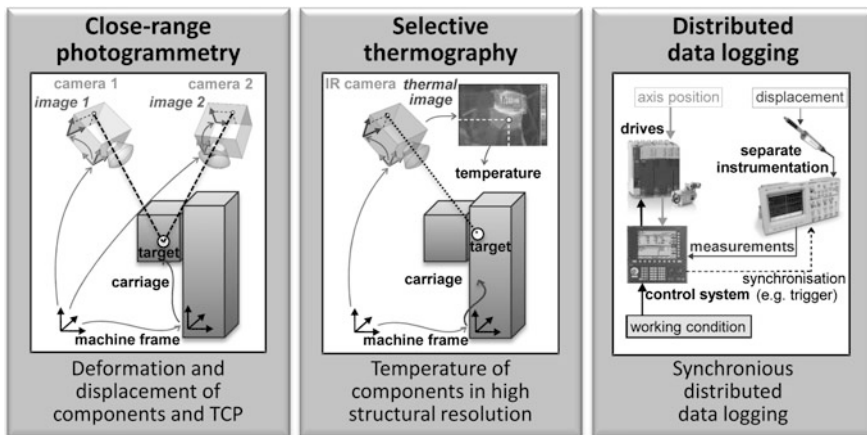


Fig. 21.1 Measuring methodology for efficient analysis of thermo-elastic behaviour according to Großmann (2013a, b)

The measuring methodology according to Fig. 21.1 elaborated in the subproject can be used to analyse complete machine tools and large-sized machine tool sub-assemblies even under working conditions and with minimal instrumentation effort. As a result, the measuring methodology offers a way to generate data for the adjustment of simulation and correction models (for instance, in the subprojects A05, A06, A07, B05, B06, B07), for exemplary parameter identification for components in the mounted-in state (subproject B04) and, finally, to evaluate compensation and correction methods (in the subprojects C05 and C06).

21.2 Approach

21.2.1 Measuring Method of Selective Thermography

The measuring methodology of selective thermography engineered within the scope of the subproject, brings together the advantages of thermographic temperature measurement with those of photogrammetric deformation and displacement measurement [Fig. 21.2, top; comp. Großmann et al. (2013a) and Luhmann (2010)].

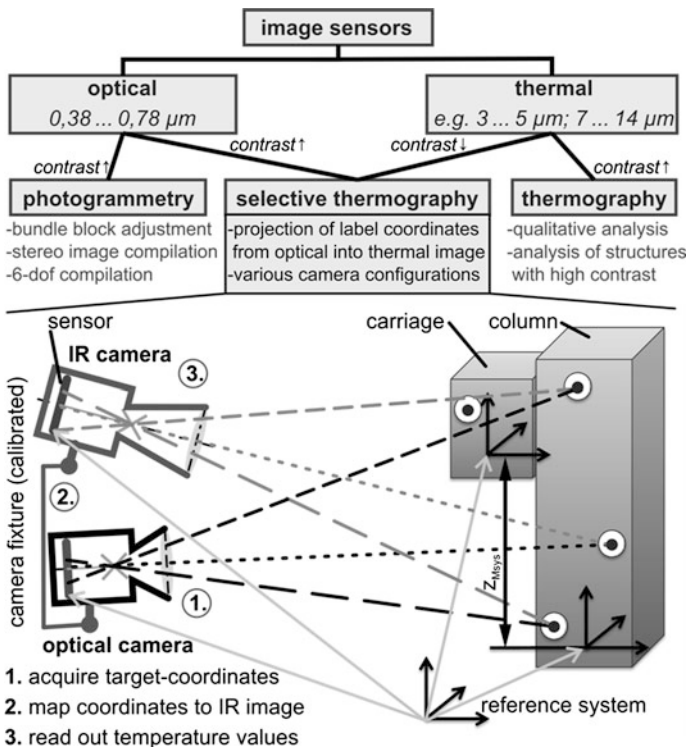


Fig. 21.2 Classification and measurement principle of selective thermography according to Großmann et al. (2013a, b)

It makes possible contactless temperature measurement even in the event of relative motion of object and thermography camera and with insufficient contrast in the thermal image (comp. thermal images in Fig. 21.7). The temperature is measured at defined targets attached to the surface of the object (e.g. printed paper labels). These adhesive photogrammetry targets exhibit a degree of emissions that is known, constant and as high as possible. The spatial location of the targets is determined in the optical image by means of photogrammetric methods (1st in Fig. 21.2, bottom). With a known relative location and orientation of both thermography camera and optical camera in a camera fixture, it is possible to determine where the pixels belonging to the targets lie in the thermal image (2nd in Fig. 21.2, bottom). Temperature is read at these pixels and assigned to the target (3rd in Fig. 21.2, bottom). Comparable approaches were also introduced by Smith (2002) and Acker et al. (2011). However, the latter rely on an areal recording of the object surface in the visible range of the spectrum by means of Speckle Texture Projection Photogrammetry or Strip Light Projection to map the thermal image on a 3D model of the object.

Selective thermography employs a wide range of photogrammetry methods. Accordingly, multiple measurement system configurations and models can be implemented. Three measurement system configurations are shown in an exemplary view in Fig. 21.3.

One can determine the location and orientation of the object to be analysed for each recording period using a 3D model that contains the 3D coordinates of the

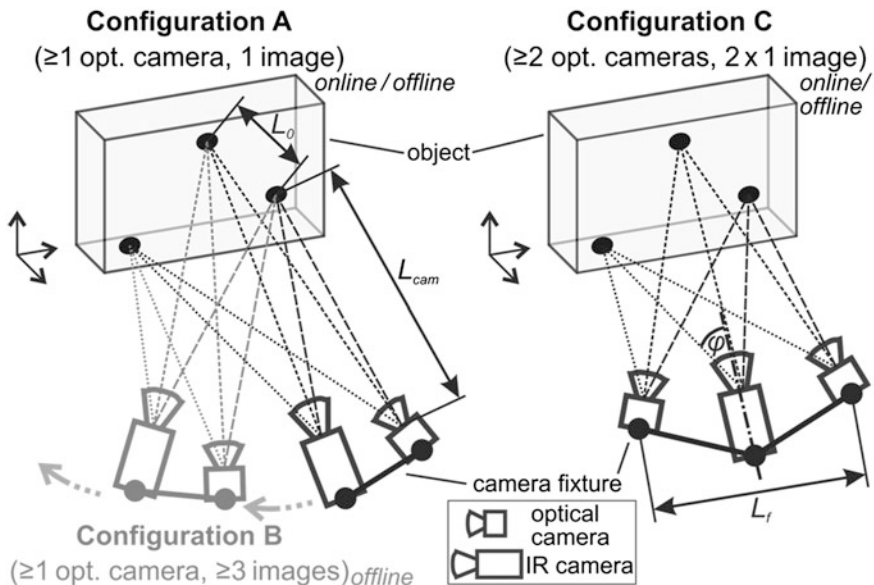


Fig. 21.3 Exemplary measurement system configurations to implement selective thermography according to Großmann et al. (2013a)

targets on the object, and a known scale reference L_0 in the image (configuration A in Fig. 21.3). The 3D coordinates can be projected onto the thermal image given the known relative orientation of optical to thermographic camera inside the camera fixture. For each target, one can also determine angle φ and its distance L_{Cam} from the thermographic camera, thereby enabling the consideration of angle-dependent emission behaviour or of the transmission properties of the medium passed through. Analysis can be conducted online during image acquisition or, as a post-process, after image acquisition, in offline mode. The 3D object model required can be obtained, for example, through preliminary calibration (coordinate measurement) by means of a photogrammetric measurement system.

If in each recording period, at least three images of an object state assumed to be constant are traced from three different perspectives, then the 3D coordinates of the targets can be determined by bundle block adjustment even without knowing the placement of the targets at the object beforehand (configuration B in Fig. 21.3). Adjustment calculation over all periods is only possible after having completed image acquisition, so it is executed offline, as is the projection of the target coordinates in the thermal images.

Having available at least two optical cameras in the camera fixture, assuming a known camera base L_f , it is possible to determine the 3D coordinates of the measured points for each period by triangulation (configuration C in Fig. 21.3). With a measurement system configuration like this, one can measure deformations in each recording period. The coordinates of the targets can also be projected onto the thermal image once after optical image acquisition. Analysis is mostly executed online, since the effort required for calculation is lower than that required for bundle block adjustment.

Both bundle block adjustment (configuration B) and triangulation (configuration C) can be expanded by using a 3D model of the coordinates of the targets attached at the object (comp. configuration A), thus making it possible to find the object's position and orientation.

21.3 Results

21.3.1 Preliminary Investigations and Photogrammetric Deformation and Position Measurements at the Test Bed

The photogrammetric measurement system DPA (Digital Photogrammetric Analysis) by the firm AICON 3D Systems GmbH was used for measurements at the test bed (see Chap. 1) to evaluate the performance of commercially available systems. Figure 21.4, left, illustrates the machine structure equipped with targets, whereas the point cloud recorded is shown in Fig. 21.4, right. When using the manually guided sensor (high resolution digital camera Nikon D3x) for image acquisition from

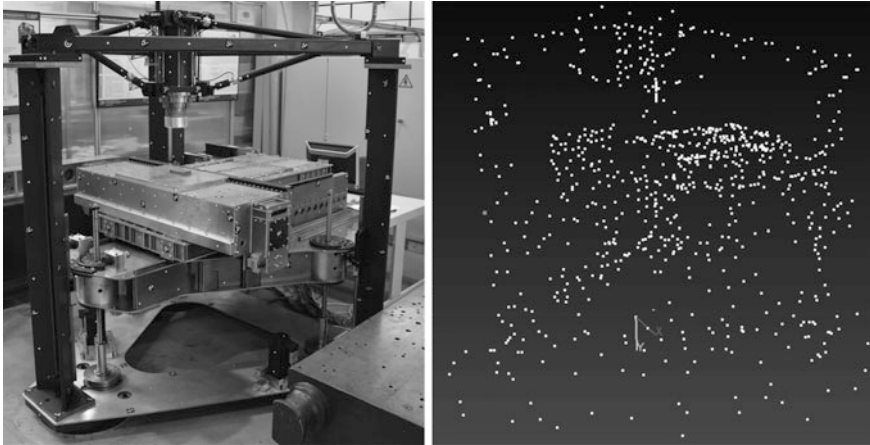


Fig. 21.4 Photogrammetric measurement by means of AICON DPA at the test bed *left* Photo from the series of images; *right* Recorded point cloud

various perspectives, only insufficient accuracy values could be reached in deformation measurement because of thermal changes during the recording time (approx. 10 ... 30 min) and because of varying picture sets. The position of individual moving subassemblies could only be determined with difficulty through the later clustering of the associated measured points in the point cloud and, according to deformation measurement, was too inexact. Brecher (2013) achieved deviations in the range of 10 μm by means of a stationary two-camera-stereo system by the same manufacturer, but with a smaller volume to be measured. However, he only determined the coordinates of the individual measured points, rather than the positions of the moved subassemblies.

The authors' own preliminary tests to evaluate the performance of commercially available systems, and the studies by Brecher (2013) clarify the potential of the photogrammetric recording of thermally affected deformations and displacements on machine tools. The investigations open up issues in research in terms of the optimization of measurement system configurations (number and allocation of cameras) and the extension of the measurement models, for instance, to consider kinematic constraints.

First, selective thermographic temperature measurement, as well as photogrammetric deformation and displacement measurement, were investigated separately at test objects with a simple structure (machine column and Hexapod MiniHex). Two series of measurements based on fundamental studies on the development of software tools and the calibration of measurement systems are introduced in the following chapters.

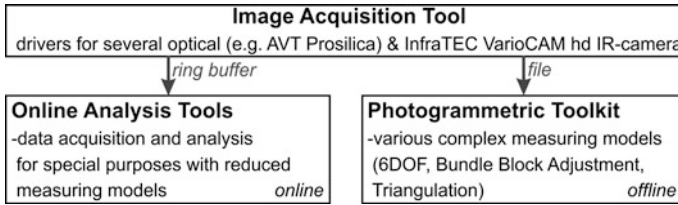


Fig. 21.5 Software tools to execute and analyse photogrammetric and selective thermographic measurements

21.3.2 *Development of Software to Execute and Analyse Photogrammetric and Selective Thermographic Measurements*

Appropriate software tools were created or refined for the execution and analysis of photogrammetric and selective thermographic measurements. Figure 21.5 gives an overview of the tools applied at the Institute for Machine Tools and Control Technology (IWM). The data recording tool was enhanced by a driver and live image display for the high resolution thermography camera InfraTEC VarioCAM HD.

The photogrammetric toolkit engineered at the IWM and introduced, among others, in Großmann et al. (2012a), was added for selective thermography (Fig. 21.5, right). With the toolkit, camera fixtures can be calibrated and measurements can be analysed by means of extensive measurement models. The toolkit relies on available image data. This means that analysis is conducted offline.

Online analysis tools tailored to the measurement task (Fig. 21.5, left) make it possible to immediately process the image data read from the ring-buffer and to store only the results obtained from it. This strategy makes sense in measurements with less complicated measurement models, but with huge data volumes, for instance, due to the long duration of measurement or the high image acquisition frequency.

21.3.3 *Characterisation of Targets and Design of a Procedure to Calibrate a Camera Fixture*

Fundamental investigations of the characterisation of selected materials and surface coatings as well of the emittance behaviour of target materials were conducted on a test specimen that was heated in a defined manner, [see Großmann et al. (2013b) for description of test specimen and experimental setup]. The usability of self-sticking paper targets (adhesive photogrammetry targets) for photogrammetric deformation and displacement measurement, as well as thermographic temperature measurement, could be verified. In addition to adhesive targets, tests were also done using

targets on magnetic films and active infrared targets (SMD resistors and IR LEDs). However, these are only usable to a limited degree for selective thermography [see Großmann et al. (2013b)].

A technique able to calibrate the camera fixture needed for selective thermography was developed and applied to two camera fixtures [see Großmann et al. (2013b, c)]. The calibration gauge required has to implement “combined” targets visible both in the optical and the thermal images. Calibration delivers sufficiently high accuracy to assign the targets in the thermal image. Calibration inaccuracy values are specified in Großmann et al. (2013d).

21.3.4 Selective Thermographic Temperature Measurement of a Machine Column

The temperature field of the machine column introduced by Großmann et al. (2012c, d) was measured to evaluate the measuring method of selective thermography. Thirteen heating foils attached on each guideway that can be switched individually serve as the thermal load (see Chap. 1 on the experimental setup). Emulated power dissipation corresponds to a spindle head movement of approximately 20 m/min, which is first applied in the bottom range of both guideways (area A in Fig. 21.6) and later in the upper area of the guideway (area B in Fig. 21.6).

The lateral walls and the back side of the machine column are equipped with a total of 20 Pt100 temperature sensors that are attached, as well as six air temperature sensors and two temperature sensors to record the base temperature for commensurable measurement of the temperature field. The selective thermographic temperature measurement is carried out on 17 coded adhesive targets, 7 of those are located at maximal distance of approximately 50 mm to a Pt100 temperature sensor, thus making possible a qualitative comparison of the measured temperature values (see Fig. 21.6 middle and Chap. 1). An AVT Prosilica GX6600 ($6,576 \times 4,384$ pixels) camera was employed as the optical camera. An InfraTec VarioCAM HD ($2,048 \times 1,536$ pixels with resolution enhancement, thermal resolution 0.05 K) was applied to thermography (see Fig. 21.6 right). The measurement system configuration corresponds to the configuration A in Fig. 21.3. However, analysis was conducted after image acquisition (offline) by means of the photogrammetric toolkit. Before starting the test, the machine column equipped with targets was calibrated by means of the photogrammetric measurement system AICON DPA in order to determine the 3D coordinates of the targets and to assign them to the 3D column model.

In Fig. 21.7, the temperatures recorded exemplarily for two selected temperature sensors (T21 left/T26 right column side wall) in a tactile and thermographic manner at next nearest targets are depicted as a function of time. Optical and thermal images with the highlighted target centre points were each mapped for four periods. Additionally the diagram shows the temperature curves calculated for both

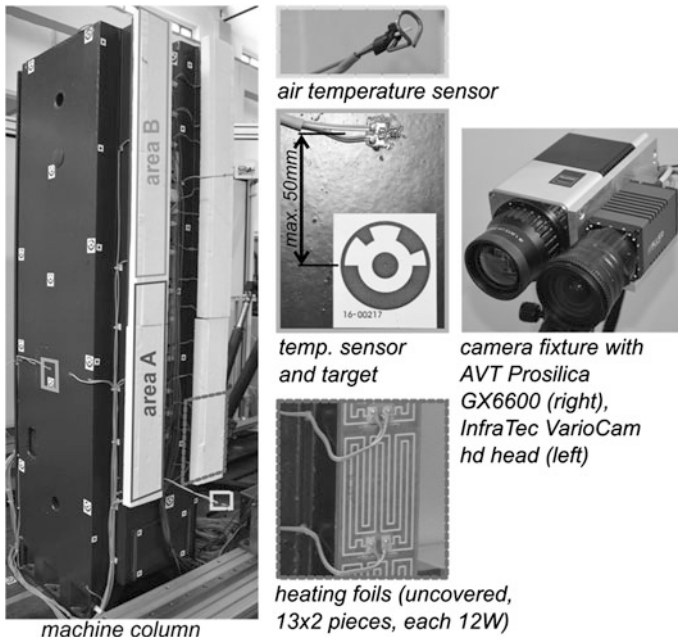


Fig. 21.6 Test setup for machine column analysis by means of selective thermography according to Großmann et al. (2014)

temperature sensors by means of a reduced-order thermal FE model (see Chap. 7) for detail on the MOR-Simulation).

It is also necessary to take into account a slight systematic deviation in the measured values due to the distance of the points measured in a thermographic and tactile manner (see Fig. 21.6 middle).

Additional tests are planned to quantify the achievable measuring inaccuracies.

The measurement described outlines the potential of selective thermography for contactless temperature measurement. It was possible to measure the temperature field in a contactless manner on three sides of the machine column with minimal instrumentation effort (sticking on the adhesive targets and photogrammetric calibration of the targets' coordinates at the structure). A deviation of less than 0.5 °C from the temperature values acquired in a tactile approach was achieved under the existing unfavourable boundary conditions. However, the accuracy potential of the measuring method is far greater.

Adjusting the simulation and measured results (see MOR-Sim in Fig. 21.7), an application was described in which selective thermography—thanks to less instrumentation effort in conjunction with high structural resolution—substantially contributes to the improvement of the machine behaviour analysis along the thermo-elastic functional chain.

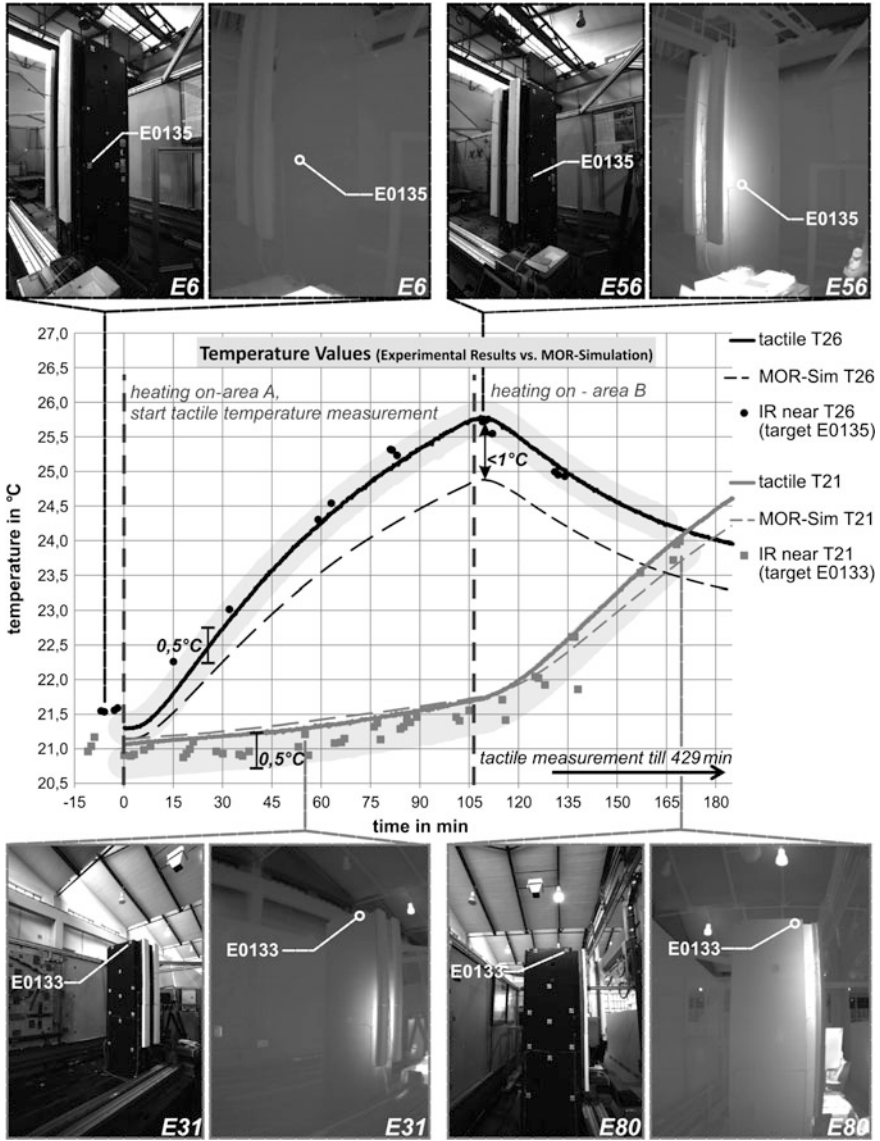


Fig. 21.7 Results of the selective thermographic temperature measurement at machine column according to Großmann (2014)

21.3.5 Photogrammetric Measurement of Thermally Affected Displacements on a Hexapod

Thermally affected displacements were captured by means of a photogrammetric measurement system configuration on the MiniHex (see Chap. 1 and Kauschinger 2006). In Fig. 21.8, left, the test setup given by Großmann et al. (2013c) is shown.

To measure displacements and inclinations, three cameras (AVT Prosilica GC2450 with $2,450 \times 2,050$ pixels) were attached to the baseplate, and three cameras were affixed to the platform (AVT Manta with $1,280 \times 9,64$ pixels) (see Fig. 21.8). The cameras on the baseplate have a convergent visual field and thus make it possible to measure the relative platform position (displacement) with high accuracy. The cameras on the platform cover as a group the largest possible visual field (divergent visual field) and thus provide high accuracy in the measurement of the relative angle (inclination) between baseplate and platform. The camera system is self-calibrating, so that 10 various positions were approached for calibration [compare Großmann et al. (2013d)]. Figure 21.8, right, shows the representation of the targets' 3D coordinates and the allocation of cameras after completed calibration. The temperatures of the bearings, ball nuts and the tubes of the rod axes were each measured in a tactile manner and recorded by means of the machine tool control (according to distributed data logging in Fig. 21.1, right). To warm up the machine structure, each rod axis was moved out and retracted again in rapid traverse for 30 times within one load cycle. The traversed path is 250 mm for each axis (see Fig. 21.9, right top). Afterwards, a photogrammetric displacement measurement was carried out automatically in the starting position (see Fig. 21.8, left). These load cycles were repeated 15 times, after which it was switched over to the

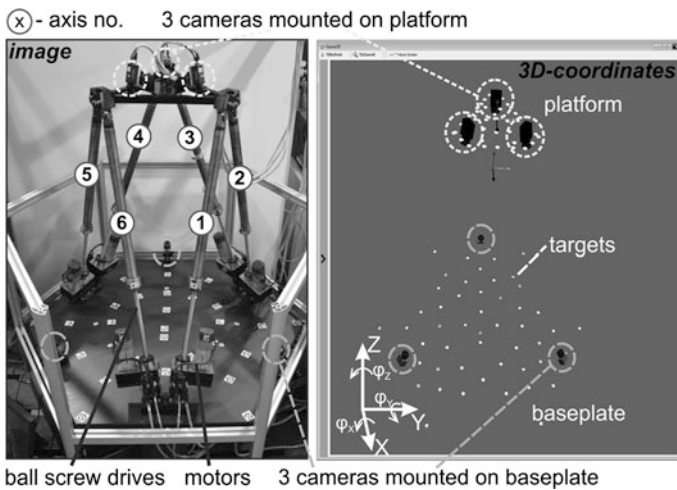


Fig. 21.8 Test setup for the photogrammetric measurement of thermally affected displacements on a hexapod [compare Großmann et al. (2013d)]

next rod. In this way, each rod axis is charged with a load over approximately 12 min and can finally cool down over a period of about 60 min.

Figure 21.9 shows a cutout of the series of measurement lasting altogether approximately 8 h. Figure 21.9, top includes the temperatures measured in a tactile manner (distributed data logging) on the ball nuts of the rod axes. The 15 load cycles on each of the individual rod axes are unambiguously mapped in the temperature curves.

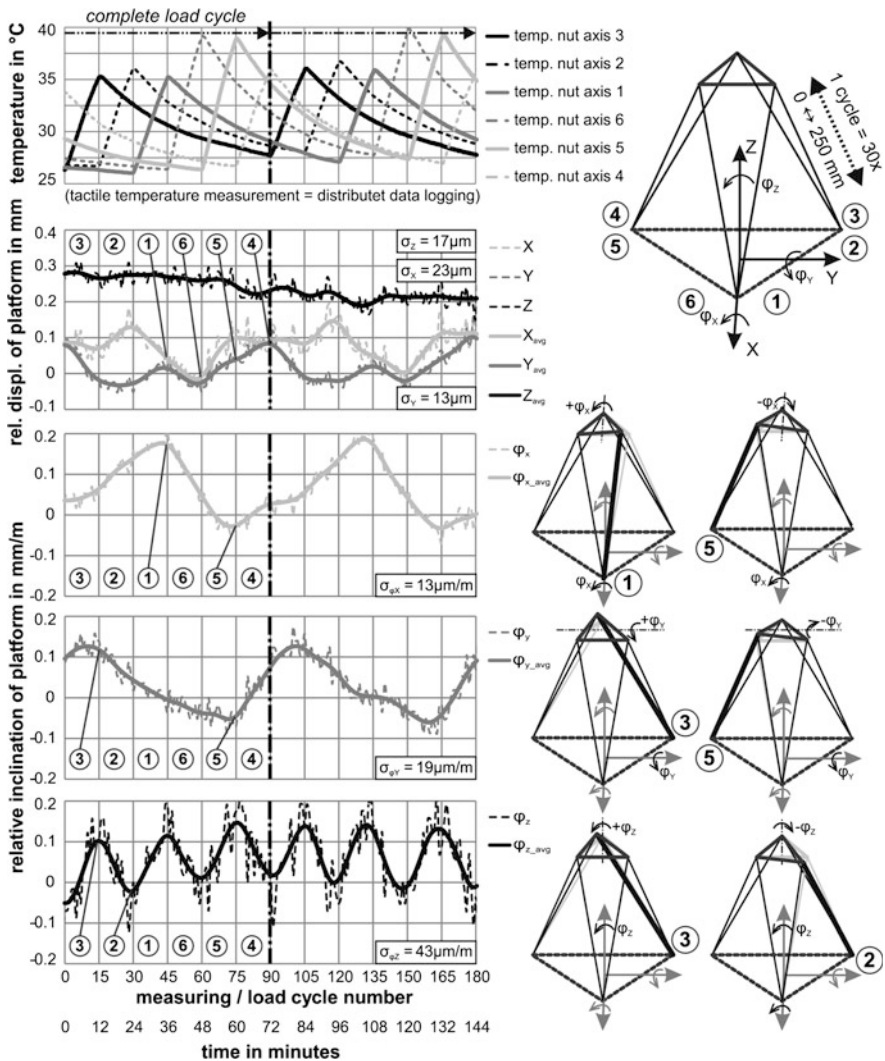


Fig. 21.9 Results of photogrammetric displacement measurement at MiniHex

Whereas the displacement of the platform on the Z axis remains almost constant except for a long-term trend, the load cycles are periodically represented on the X or Y-displacement (see relative displacement of the platform in Fig. 21.9). The displacement in the negative X direction due to warming up of the rod axes 1 and 6 or the displacement (translatory movement) in positive Y direction due to warming up of the rod axes 5 and 4 can be clearly traced.

Thermal expansion of the individual rod axes is obvious in view of torsion of the platform across the Z axis (Fig. 21.9, bottom). Warming of the rod axis 3 results in torsion of the platform in positive φ_Z direction. Warming of the rod axis 2 effects a reverse rotation of the platform in negative φ_Z direction. This sequence is repeated periodically with each change to the next rod axis. Greater periods that correspond to a complete revolution of all six rod axes appear for the inclination of the platform across the X- and Y-axes (see Fig. 21.9, middle).

The results of the series of measurements on the MiniHex (Fig. 21.9) demonstrate the way to measure relative displacements and inclinations on machine tools by means of close-range photogrammetry. There is no problem with, and no limitations on, recording the kinematic deviations in all six degrees of freedom, except for the visibility of targets. Measuring inaccuracy is sufficiently low.

Still lower measuring inaccuracy values can be obtained by an optimisation of the measurement system configuration, which also qualifies the method, as described in Großmann et al. (2012b), also for serial kinematic structures with very low positioning inaccuracy values. The existing series of measurements also clarifies the influence of example-specific variations of the parameters of individual machine components (compare subproject B04). Thus, on the ball nuts of the rod axes 6 and 5, a greater rise in temperature occurs than in the other axes.

21.4 Classification of Outcomes in the CRC/TR 96

In the future, the measurement methodology introduced makes it possible to correlate the temperature field with deformation and displacement, taking into account the operation state of the characterised machine by means of distributed data logging. This allows for a holistic analysis of the machine behaviour along the thermo-elastic functional chain. The measurement methodology primarily benefits those users who have to analyse whole machines under operation conditions “on site”. The methodology provides a major contribution to the adjustment of simulation and correction models (such as in the subprojects A05, A06, A07, B05, B06, B07), for object-related parameter identification, particularly for components in the mounted-in state (subproject B04) and finally the evaluation of compensation and correction methods (subprojects C05 and C06).

The measurement methodology introduced in this paper provides a crucial methodological contribution to the CRC/TR 96.

21.5 Outlook

The measurement methodology according to Fig. 21.1 is used for the comprehensive thermo-elastic analysis of the MiniHex (see Fig. 21.8) and, at the end, implemented at the test bed (see Fig. 21.4) to demonstrate its usability even under poor boundary conditions. Furthermore, additional investigations to quantify the measurement inaccuracy in selective thermographic temperature measurement are planned. The measurement system configurations described in the paper and adequate software tools will be continuously improved and refined.

The techniques to consider the emittance of the targets and the influence of the radiation background are being refined in order to increase the accuracy of the selective thermographic temperature measurement.

In the future, at the test bed, different compensation methods are to be integrated, and correction methods are to be implemented on the PC-based control system by using distributed data logging. The comparison of the methods in terms of their compensation or correction effect is carried out by means of a photogrammetric measurement system configuration installed at the test bed in a fixed manner. Moreover, this measurement system configuration is the basis for a correction approach based on metrology, which will be developed in the third project stage of subproject C06. Within this approach, geometric-kinematic deviations at defined intervals, such as, for instance, in machining idle times are measured photogrammetrically, and correction values for the feed drives are calculated using a kinematic model and corrected.

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