Thermal Error Analysis and Compensation of an LED-CMOS Camera 3D Measuring System

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Abstract

Photogrammetry measuring systems using LED targets and CCD/CMOS cameras are gaining application in industry. Compared with conventional CMMs (coordinate measuring machines), they are easily portable, versatile and convenient to use. Like most precise measuring devices, these camera systems also suffer from performance degradation when temperature deviates from standard condition. This paper introduces research work performed on a twin-camera 3D measuring system regarding its measurement performance during environment temperature fluctuations. An artefact is developed to provide stable reference for drift identification and performance verification. This artefact is used together with temperature sensors to study the thermal drift behaviours of the camera system. A thermal drift model is built to calculate and compensate the thermal drifts. After compensation, the thermal drifts (of 3D length measurements) are reduced to approximately 30% of their original sizes in a temperature range of 9 centigrade (16.5˚C ~ 25.5˚C), which enables the measuring system to work with enhanced performance under typical industrial environments.

1. Introduction

LED-CCD/CMOS Camera 3D measuring systems (referred to as "camera systems" in the following text) are kinds of photogrammetry measuring systems applying triangulation measurement principles [1, 2]. Their ability to measure more than one points at a time, to measure remotely and without contact, their compact sizes and portability are advantages making them more and more popular in metrology fields. Therefore, manufacturers and users often call them "portable CMMs".

A current trend in industry is to locate the measuring devices directly nearby the production processes, which places high demands for the measuring performance under varying industrial environments [3, 4]. During measurements, a conventional CMM suffers errors from non-standard environmental temperatures [4, 5], so does a camera system. The thermal behaviour of conventional CMMs has been studied for many years, and successful methods have been developed to reduce the thermally induced errors, whereas similar research on the camera systems is still limited.

This paper presents research work on a twin-camera LED-CMOS system. Initial experimental results show that this camera system is much more temperature sensitive than conventional CMMs. Based on analysis of collected data, better understanding of the camera system's thermal behaviour is obtained, and a multi-linear regression model is developed to compensate the thermal errors.

2. The Camera System

The twin-camera LED-CMOS 3D measuring system (Krypton K100 System) under study is shown in Fig.1. This system includes a twin-camera unit, a tripod with an orientation joint, LED targets, interface PC and other accessories. The working volume of this measuring system is about 2 m^3 with an irregular shape [6]. During measurements, the LED targets are attached to the object of interest, and the object's motions in the camera coordinate system can be detected by tracing the motion of the LED targets. The camera system outputs 3D coordinates of the LED targets just like a CMM outputs the coordinate of the touch-trigger points.

Up to 12 targets can be traced by this camera system at the same time. To measure an object's 6D (3 degrees of translation, 3 degrees of rotation) displacements relative to a reference objective, 3 LED targets have to be attached to the displacing object and 3 more to the reference object. The large number of possible LED targets is also an advantage to implement multi-points measurements in thermal error related tests.

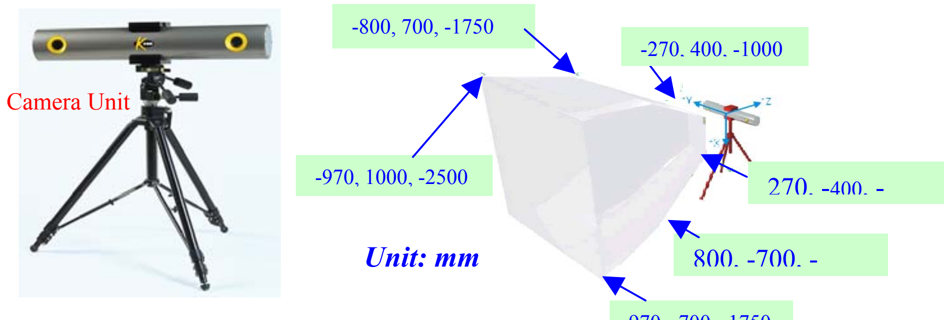

Fig.1 K100 Camera System and Its Working

3. Temperature Influences

Found in experimental measurements, performance of the camera system is very sensitive to the environmental temperature influences [7]. The camera system was calibrated and optimised at 20˚C, but a little deviation from this optimal temperature may induce large measurement errors. Basically, the camera system suffers from two types of thermally induced measurement errors: thermal errors in calibration and thermal errors in field applications.

During the camera system's calibration procedures, it is hard to maintain a perfect 20˚C environmental temperature. The thermal disturbances will bias the calibration data and become a part of the system uncertainty after calibration. During field measurements, because of the larger fluctuation of the environmental temperature, the camera system suffers from even more significant thermal drifts. Therefore, to enhance the overall performance of the camera system and widen its applications in industrial environments, systematic studies and compensation techniques for thermally induced errors are indispensable.

4. Test Set-up

Temperature information is important for analysis and compensation of thermal errors on the camera system. To monitor the temperatures of the environment and the camera system comonents, four Dallas Semiconductor DS1624 digital (crystal oscillator) temperature sensors are added to the camera system. Their resolution is 0.03125˚C, and the guaranteed accuracy is better than 0.5˚C [8]. One sensor is placed in the room air, and the other three are placed inside the camera housing (as shown in Fig.2, one sensor on each camera and one sensor on the supporting structure in the middle).

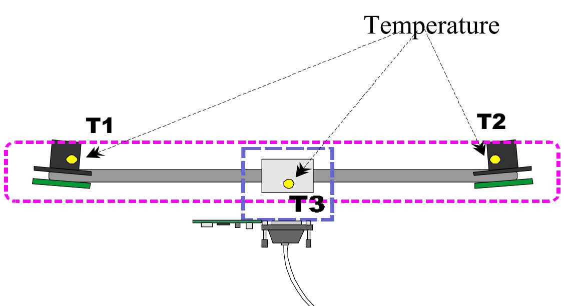

Fig.2 Temperature Sensors

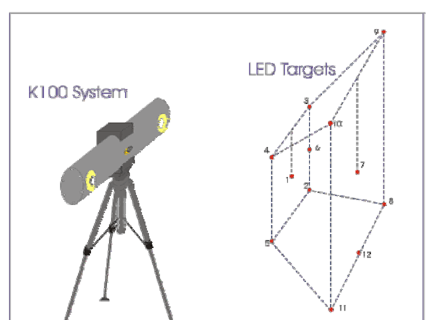

Fig.3. Test Set-up

During the tests, the camera system is placed in a room with temperature control, in which the air temperature could be changed between 16˚C and 26˚C to simulate the temperature changes in industrial environments. As temperature changes (by about 10˚C), deformations of the various supports (the floor, the tripod supports of the camera system and the supports of the objectives) will induce changes to the position links between LED targets and the camera system. This makes it difficult to directly trace the measuring accuracy of absolute positions (single point accuracy). Therefore, an artefact is developed to provide the camera system with a stable reference for indirect error measurements. This artefact is a rigid frame made in INVAR rods (Fig.3). 12 LED targets are attached on the frame at different positions. The dotted lines represent the INVAR rods, and the numbered points stand for the LED targets.

5. Thermal Error Compensation

Due to the INVAR rods' very low thermal expansion coefficient (about 1 µm/m/˚C), the physical distance between every two LED targets can be regarded as a constant value during the tests (Fig.3). Since the 12 LED positions are always measured at the same time, the measured distances are only influenced by the camera's own thermal behaviour but not by the changes in the position link between the camera system and the artifact (LED targets).

During preliminary tests, it is found that the measured distances are quite repeatable if the temperatures are kept stable [7]. The variation on 1m distance is in a range about ±30µm (1σ). To define the "exact" distances between these LED targets, a very stable environment temperature at 20˚C is maintained (±0.2˚C). After a sufficiently long initial self-heat-up time (about 2 hours) of the camera system, the measurement results stablise. The measured distances in this stable state are defined as "exact" distances.

Then the room temperature is changed to simulate an industrial environment. The temperature changes are made large enough (from minimum16.5ºC to maximum 25.5ºC) to cover normal work shop temperature ranges. For each test, different heating/cooling patterns (temperature fluction) are used, and the 12 LED targets are put to different sets of positions on the INVAR structure. The purpose is to collect sufficient and reliable data for the thermal behaviour analysis. The measured distances during the tests will be compared with the "exact" distances, and the following formulas can be obtained:

$$(D(1,2)+\Delta D(1,2))^2 = (X1+\Delta X1-X2-\Delta X2)^2 + (Y1+\Delta Y1-Y2-\Delta Y2)^2 + (Z1+\Delta Z1-Z2-\Delta Z2)^2 \qquad (1)$$

$$\Delta D(1,2)\times D(1,2) \approx (\Delta X1-\Delta X2)\times(X1-X2) + (\Delta Y1-\Delta Y2)\times(Y1-Y2) + (\Delta Z1-\Delta Z2)\times(Z1-Z2) \qquad (2)$$

Remarks: ***D*** is the exact distance between the two targets.
ΔD is the 3D drift of the measured distance.
$D(1,2)+\Delta D(1,2)$ is the length measured by K100 system.
X/Y/Z is the x/y/z position of a target.
$\Delta X/\Delta Y/\Delta Z$ is the drift in x/y/z position.
$X1+\Delta X1/\ Y1+\Delta Y/\ Z1+\Delta Z1$ is the x/y/z position measured by K100 system.

For each ΔX, ΔY and ΔZ, multi-linear models with various parameters are studied. With the measured results, the correlations between the candidate parameters and thermal drifts are analysed, and the most contributive parameters among them are chosen to construct the error models. It is found in the analysis that the drifts are not only dependent on temperature changes, but also strongly correlated to the LED targets' positions. The modelled thermal errors can be briefly expressed by the following equations:

$$\Delta X = fx(T0, T1, T2, T3, X, Y, Z, R)$$
$$\Delta Y = fy(T0, T1, T2, T3, X, Y, Z, R)$$
$$\Delta Z = fz(T0, T1, T2, T3, X, Y, Z, R)$$

Remarks: $R = \sqrt{X^2 + Y^2 + Z^2}$
fx, fy, fz are muti-linear functions of the enclosed variables

$$\Delta D(1,2) \approx ((fx_1 - fx_2)\times(X1-X2) + (fy_1 - fy_2)\times(Y1-Y2) + (fz_1 - fz_2)\times(Z1-Z2))/ D(1,2) \qquad (3)$$

Each error component (ΔX, ΔY or ΔZ) is sensitive to a part of these parameters and their composites, so the composed multi-linear model of ΔD has mixed parameters from all the three error components. Due to the large number and complexity of the parameters, careful iterative selection of contributive parameters is required. Using multi-linear regression methods and the data collected in the tests, the coefficients of the model can be computed. To compensate the thermal drifts in measurements, a program is developed to use the error models, the measured temperatures and coordinates to calculate errors (Δ***X***, Δ***Y*** and Δ***Z)*** of the measurements. Then it subtracts the errors (Δ***X***, Δ***Y***, Δ***Z)*** from the measured coordinates to obtain corrected coordinate values.

To verify the compensation results, additional tests are run with new temperature patterns and LED positions, which are totally different to the tests used to calculate the model parameters. The results indicate that during temperature fluctuation between 16.5ºC and 25.5ºC, the developed compensation method can reduce thermal errors (in sense of 3D distance) down to 30% of of their original sizes. Fig.4 shows the temperature fluctuation of one test. Fig.5 shows the error on the measured distanced between two LED targets (about 1.5m) before and after compensation in the temperature changes.

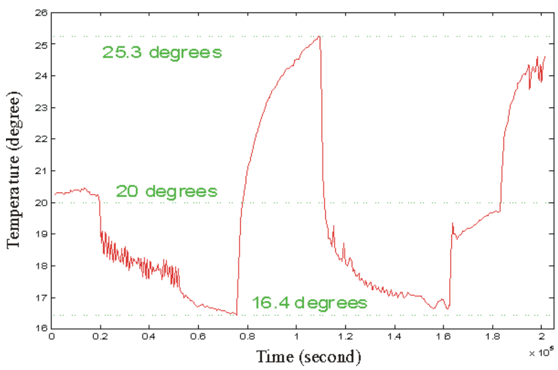

Fig.4. Room Temperature Pattern in Verification Test

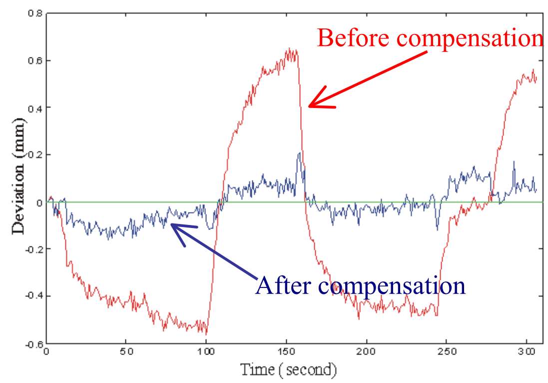

Fig.5. Compensation of Results before and after Compensation

6. Conclusion

The performance of LED-CCD/CMOS camera measuring devices could be significantly degraded by varying environmental temperatures. In order to gain wider application in industrial environments, it is necessary to improve their measurement performance against the disturbances from changing temperature. The thermal error compensation discussed in this paper is based on mathematical models and software compensation. The results show that the software compensation methods are efficient and cost-effective approaches to enhance the measurement performance of the camera system in field application.

Acknowledgement

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