Behaviour and accuracy specification – study on an LED-CMOS camera 3D measuring system

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Abstract

3D photogrammetry measuring systems using LED targets and CCD/CMOS Cameras are gaining wider application in metrology fields. They are often used as portable CMMs in different industry sectors. Because of the similarities between these camera systems and conventional CMMs in dimensional measurements, the accuracies of these optical systems are normally specified using the well-established methods for conventional CMMs. However, the analytical and experimental results introduced in this paper show that the current accuracy specification methods are not well representing the accuracy of these camera systems. They show quite different field performance than conventional CMMs, due to the systems’ specific characteristics. As a possible solution, in the latter part of this paper, a more comprehensive accuracy depicting method for these camera systems is suggested in order to give closer-to-fact specification.

1 Introduction

The advance of optical 3D metrology has been speeded up by rapid growth of computational power and opto-electronic technology during the last three decades [1,2]. One type of optical 3D measurement device commonly used for medium to large scale metrology are 3D Photogrammetry measuring systems using LED targets and CCD/CMOS Cameras (referred to as “camera systems” in this paper): see example on Figure 1. Although the accuracy of these camera systems is not as good as current accurate CMMs (Coordinate Measuring Machines), they still have many advantageous features. For example, their
ability to measure more than one point at a time, remote measurements without contact, compact size and portable components are all making them competitive. Their ever wider application has already entitled them to be called “portable CMMs” with potential to enforce/replace many traditional measuring methods and to explore new application areas. Therefore, proper methods to quantify the camera systems’ performance and accuracy (or uncertainty) of measurement become increasingly important.

As measuring systems, conventional CMMs and camera systems share many similarities in measurements, but they also have many differences in measuring behaviours due to the different principles and structural configurations they apply. Some of the accuracy specification and performance verification methods defined for conventional CMMs can be similarly applied on camera systems [3, 4]. On the other hand, camera systems have some special characteristics requiring special treatments in accuracy description and performance evaluation. Therefore, based on research with a twin-camera system, this paper shows the necessity for some supplements to the currently applied accuracy-guaranteeing techniques and proposes a possible solution.

2 Current accuracy specification methods

The accuracy of a CMM can be specified in terms of maximum permissible error (MPE$_E$) in one of the following formats [3]:

\[ MPE_E = \pm \min(A + L/K, B). \]  
\[ MPE_E = \pm A + L/K. \]  
\[ MPE_E = \pm B. \]

MPE$_E$ is maximum permissible error for size measurement expressed in micrometres.
A is a positive constant, expressed in micrometres and supplied by the manufacturer.
K is a dimension less positive constant supplied by the manufacturer.
L is the measured size, in millimetres.
B is the maximum permissible error in micrometres, as stated by manufacturer.

These formats have already been standardised and widely accepted by conventional CMM providers and users for a long time. In order to keep conformance to the well established CMM standards, the LED-CCD/CMOS 3D CMM manufacturers therefore adopt similar formats to describe their products’ performance [5], [6].

However, the working principles of these optical measuring systems imply that errors vary remarkably at different measuring positions and at fluctuating temperatures. This is a notable point in which these camera systems differ from conventional CMMs, which means that it is not always proper or sufficient to directly apply accuracy specification formats of CMMs to camera systems. Performance tests on a LED-CMOS camera system also show very different error variances at different measurement points and under shifting environmental conditions. All these results imply that the direct application of the previous accuracy specification formats can’t always meet the exact performance of the
camera systems. Systematic analysis and experimental tests have been carried out in order to find better solutions.

3 Major causes of position dependent errors – general analysis

Theoretical analysis helps in identifying and reasoning on errors. There are three major conclusions, which can be drawn from the analysis.

1. Photogrammetry measurements require imaging the same object from at least two different positions. This paper focuses on the systems using two or more simultaneously imaging cameras. The positions where the cameras are placed are an important factor to the system accuracy. To reduce the computing intensity and simplify the production, it is common to fix them on a single support and more or less in parallel, but doing this causes a loss in accuracy. In particular, the axis corresponding to the system’s line-of-sight will appear to be less accurate than the others.

2. The number of pixels of a CCD/CMOS camera is fixed. Basically, a camera has a constant “angular resolution” when measuring targets. That means that the resolution of the system at near field is higher than at far field. Furthermore, small instabilities of the camera system will be amplified to relative big errors at long distances. The direct consequence of this problem is that repeatability degrades with distance.

3. Temperature is a very critical contributor to the errors of the camera systems. All the components on the camera system may shrink, expand or distort due to temperature changes. The thermal displacement of the individual cameras’ relative position has a big impact to the measurement, because all the coordinate calculations rely on this relative position. Having noticed this problem, some companies have already applied INVAR material to their camera systems to provide a stable connection for the cameras. Nevertheless, the thermal effects associated with deformation of lenses, heating electronic boards and other expansible materials are still significant. Because of the problem discussed in the

![Figure 1: Camera System (right) and an LED Target (left)](image)
previous passage, the thermally induced errors will vary according to the targets' positions in the measuring volume.

There are also other influences (e.g. vibration, light diffraction), which are hard to be clearly estimated. However, these influences are less significant compared to the major causes discussed above.

4 3D Camera measuring system under test

A twin-camera LED-CMOS 3D measuring system (Krypton K100 System) as shown in Figure 1 was studied in the metrology laboratory of PMA, Catholic University Leuven [6]. This novel system includes a twin-camera unit, a tripod with an orientation joint, LED targets and other accessories. The working volume of this camera system is about 2 m³ with an irregular shape as shown in Figure 2. During measurements, the LED targets are attached to the objects of interest, and the targets' motion within the coordinate system will be measured. When several LED targets are used they are sequentially illuminated by the controller of the measuring system. The measuring system outputs coordinates of the targets just like the output of a CMM equipped with a touch trigger probe.

To perform accuracy related tests a reference system must be built. Figure 3 depicts one test set-up used to collect measurement data for analysis of performance issues. One (or two) LED targets are put on the arm of the CMM. Since the CMM is much more accurate than the K100 system, it can be used to provide positioning references for the camera system. When the arm of the CMM moves, the whole machine undergoes slight inclination changes due to displacement of the gravitational centre of the machine's moving parts (the legs, saddle, arm) and its flexible damping supports. Therefore, to avoid this influence, the camera system is directly connected to the granite table by a supporting structure, instead of putting it on its tripod standing on the floor.
5 Causes of position-dependent errors – experimental tests

A few measurements are designed for different purposes. Corresponding to the previously performed error analysis, the test results are presented consequently as follows.

1. The two cameras of the K100 are placed along its Y axis. The X, Y axes of the camera’s CMOS chips have approximately the same directions as the X, Y axes of the camera system. With this layout, the measured X, Y coordinates of targets will be more accurate than the measured Z coordinates. During the measurements, the CMM was commanded to move a fixed distance of 50 mm, 100 mm or 200 mm along a single axis of the camera system. It is found that the errors on measured lengths lying in Z direction are always much bigger than those of lengths lying in X and Y directions. In other sets of tests, it is also found that the measurement repeatability in Z direction is much worse than in X and Y directions. All these observations justify the first conclusion of the analysis.
2. Due to the limitation of "angular resolution", the farther the LED targets the lower the accuracy. This problem was again witnessed in the measurements. In the tests, the CMM moves a LED target to grid points in a rectangular area (shown in Figure 4), and the camera system performs one measurement at every point. By performing best fit (least square) transformation between measured coordinates in camera coordinate system and in the CMM coordinate system, the measured points are fitted around the "exact" CMM points. The obtained results comply with what the analysis predicts. The errors (X, Y and Z) measured in the far field are a few times bigger than those measured in the near field. The same holds with the repeatability of the measurements. Figure 5 shows the Z direction errors (and repeatability) of the measurements at two positions (at distances of 1.4 m and 2.3 m). In this test, the CMM arm (with LED targets) was continuously moved between two positions in the grid area. Measurements at nearer side appear to be much more accurate and repeatable.

3. It is also observed in the grid tests that the camera system’s X or Y error increases with the absolute value of (the target’s) X or Y position respectively, when Z position is kept constant. As a consequence, the Z error also increases with both X and Y position since the error in Z is influenced by any inaccurate measurement of the X or Y position. The measurement also shows that when large temperature changes occur during the measurements, the relevant errors turn out to be bigger. This is just compliant to what has been concluded from an analysis of thermal effects on the camera system.

![Monitored Drift at Two Positions](image)
6 Preliminary solutions

The previous analysis and tests have shown that the current accuracy specification methods for CMMs can hardly suffice the need of camera systems. If one uses the camera system’s overall maximum errors to define its accuracy, of course all the measurement errors will be within the specified ranges, but the users will not be aware of and take profit of the system’s higher accuracy in the near field or along certain preferable directions. If one uses the minimum errors, obviously most measurements will fall out of the stated error budgets.

Manufacturers of the camera systems understand this situation and try to adopt some improved methods to deal with this problem. A solution to this problem is to divide the working volume of the camera systems into a few areas (Figure 6) [7]. For each area respectively, two accuracy formulas are given in format of eqn (2). One formula indicates the single point accuracy, and the other one indicates the volumetric length measurement accuracy. Compared to a single eqn (2), this is an improvement which provides users more information when they are planning measurements.

This method is also applicable to other camera systems, but there will still be a big difference between the measurements’ stated accuracy and the exact accuracy. Some questions that remain with this method are:

What is the accuracy,
- if a length is measured along Z axis or X/Y axis?
- if a length is measured in near field or far field of a single accuracy zone?
- if the two LED targets on an objective length are in two accuracy zones?
- if the temperature changes?

7 Proposed solution

A good description of the error behaviour not only helps users to optimise their application of the measuring system, being sure of the accuracy of their measurements, but also helps the manufacturers to meet more customers’ needs. Therefore, a good description of accuracy should show anisotropic uncertainties, should present the increasing error trends with increasing distances, and should also account for temperature influences. Directly representing the uncertainties by formulas is too complex to show the users, because the errors follow high
order linear, multi-linear or non-linear relations with many variables like X, Y, Z and temperatures. It could be possible for the device manufacturer to make a complete "uncertainty map"; however, this approach not only requires quite some efforts to construct such a relatively accurate uncertainty map, but also yields difficulties to show the users a clear view. Therefore a simpler but effective solution is proposed here.

The proposed solution uses a schematic format shown in Figure 7 (with preliminary data subject to refinement). The figure shows the system’s single point accuracy (1σ values) in 20°C environment at different representative positions. Because of the symmetry of the working volume and error distribution, it is only necessary to define the accuracy at a few positions in one quarter of the measuring volume. These positions are close to the border of the working volume and on the Z axis of camera system (more points in between can be added if necessary). These positions’ coordinates as well as the X, Y and Z accuracy at these positions are marked next to each point on the accuracy graph. The single point accuracy at other positions can be approximately calculated by interpolation.

![Figure 7: Absolute Accuracy of Single Points at Representative Positions](image)

There is one additional factor, i.e. the temperature. Because of the existence of big differences among thermal errors at different positions, it is necessary to identify thermally induced error at each position. The major part of the thermal drift can be modelled and compensated by computer software according to the measured temperatures of the environment and the camera system’s components [8]. The uncompensated part of the drift will remain in the measurement as an additional part of uncertainty. Therefore, the accuracy statement at each position is altered to the format depicted in Figure 8 (taking 20±5°C as valid temperature range). The thermally induced uncertainty is defined as "µm per °C", and it will increase when the temperature deviates from 20°C. The expression will be used in the single point accuracy specification (1σ value) shown in Figure 7 to construct a complete performance quantification graph.
Figure 8: Thermally Induced Uncertainty

With the help of this accuracy specification method, users can extract enough information of the measuring system’s performance and plan the tests. Via uncertainty propagation method \([g]\), the k-σ measurement uncertainty \((U_D)\) of the distance between two LEDs at \((X_1, Y_1, Z_1)\) and \((X_2, Y_2, Z_2)\) can be quickly figured out by the following uncertainty propagation equations:

\[
U_D = k \times \sqrt{u_{1X}^2 + u_{1Y}^2 + u_{1Z}^2 + u_{2X}^2 + u_{2Y}^2 + u_{2Z}^2} \quad k = 1, 2, 3..., \quad (4)
\]

\[
D = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}
\]

\[
u_{1X} = \frac{dD}{dX1} \times u_{X1} = \frac{X_1 - X_2}{\sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}} \times u_{X1}
\]

... 

\[
u_{2Z} = \frac{dD}{dZ2} \times u_{Z2} = \frac{Z_2 - Z_1}{\sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}} \times u_{Z2}
\]

**Remark:**

- \(D\) is the measurement distance between the two LED targets;
- \(u_{1X}, u_{1Y}...u_{2Z}\) are the uncertainties specified by the accuracy graph (Figure 7 and Figure 8);
- \(u_{1X}, u_{2Y}...u_{2Z}\) are the respective contribution from \(u_{X1}, u_{Y1}...u_{Z2}\) to the total uncertainty.

### 8 Performance verification

Normally the performance verification can be done in two ways. One way is to use a CMM together with the camera system (as Figure 4 shows) to measure single point errors in the working volume (i.e. doing multiple measurements, for example 10 or 20, at each point). These single point errors are then compared to the ones specified in the accuracy graph (Figure 7 and Figure 8). Normally, this method requires a large CMM, long measuring time and matrix calculations. A more practical method is to measure stable distances provided by a CMM or by reference lengths [4]. In this case, the observed variation (1σ) will be compared to the uncertainty \((U_D)\) according to the proposed accuracy specification (Figure 7 and Figure 8) and the uncertainty propagation equations.
9 Conclusions

This paper analyses the measuring behaviours of LED-CMOS/CCD camera systems. It points out the disadvantages of the currently applied accuracy specification methods. A new accuracy definition method is proposed. It enables the manufacturers to describe the system accuracy in a more efficient way and provide the users with much more information on accuracy. This is of major benefits in selecting, planning and analysing measurements done with the camera systems.

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References