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Geometrical calibration of CMOS/CCD chip for straight laser line measurement

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Abstract

The straight laser line serves as a reference for precise alignment. By measuring the perpendicular offsets relative to this laser line, the radial and vertical position of the CMOS/CCD chip can be determined, providing an effective alignment technique for linear structures. Typical examples of such structures are magnets and other components of particle accelerators at CERN. To accurately measure an object, its position must be linked to the location of the laser spot on the chip. This link is achieved through chip fiducialisation, which establishes the three-dimensional transformation between the chip's coordinate system and kinematic mount. A three-ball kinematic mount is employed to ensure repeatable camera positioning. The mount's location is measured within the global coordinate system using a Coordinate-Measuring Machine (CMM) and a laser tracker. In this study, we determine the transformation (six degrees of freedom) between the chip and mount coordinate systems using a calibration bench, which consists of differently oriented kinematic mounts located along laser lines. Observations from the CMM, laser tracker, and laser lines are combined in a single least-squares adjustment model to estimate the transformation parameters and assess their accuracy. The results of this fiducialisation allow the calculation of the laser spot position on the chip in the global coordinate system of the alignment system.

Calibration, Geometry, Laser, Measurement

1. Introduction

Measurements relative to a straight reference line are a standard approach in alignment procedures [1]. Such a reference line can be established using an optical beam propagated within a vacuum system to mitigate the effects of atmospheric refraction. The Structured Laser Beam (SLB) is a promising candidate for establishing this straight reference line [2].

The SLB belongs to the broader category of pseudo-non-diffractive optical beams and features a transverse intensity profile resembling that of a Bessel beam. It is characterized by a narrow inner core (IC) surrounded by concentric rings. Thanks to the IC's low divergence, as small as 10 µrad, SLBs are well-suited for long-distance alignment. While theoretically capable of propagating indefinitely, SLBs have been experimentally demonstrated to maintain their properties over distances of up to 900 m [3].

The IC is measured using a CMOS chip, later referred to as the chip, which is in a camera housing without a lens. To utilize the IC's centre coordinates derived from image processing, the geometric position of the chip must be known within the external coordinate system of the sensor, defined by the fiducial points of a kinematic mount. In other words, the transformation between the coordinate system of the camera and the kinematic mount must be determined.

The optical alignment system relies on a chip equipped with a kinematic mount, enabling repositioning with sub-micron precision within the global coordinate system. In Figure 1, the SLB sensor is depicted with a kinematic mount based on a 3-ball support system. The measurement link between the 3-ball mount and the chip can be done using a Coordinate Measuring Machine (CMM) when the chip is accessible to the CMM's measurement tools. However, once the chip is installed within the camera housing, access for direct measurement becomes significantly restricted. Additionally, passive measurement, such as the CMM measurement of the chip, does not account for how the sensor detects light. For instance, determining the exact operational area of the chip matrix is challenging during passive measurements.

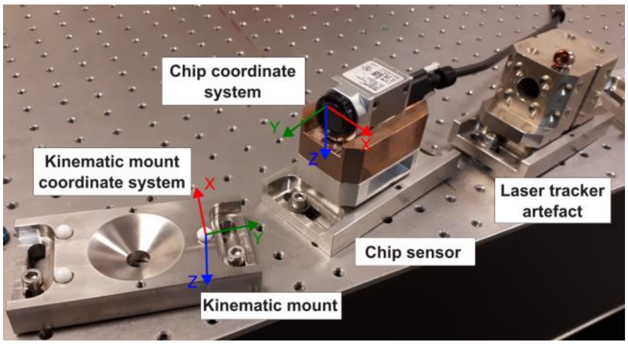

Figure 1. The kinematic mount, chip and laser tracker artefact. Both right-handed coordinate systems have a transversal x-axis, longitudinal y-axis and downward z-axis.

This paper introduces a novel geometrical fiducialisation method to facilitate the alignment using chips and kinematic mounts. The proposed method is based on a calibration procedure conducted on a calibration bench. It employs five laser lines and five camera positions on kinematic mounts to calculate the transformation parameters between the camera's coordinate system and the kinematic mount's coordinate system, along with their associated uncertainties. The calibration measurement is adjusted using a least-squares model, implemented in the in-house-developed *LGC2* software [4]. These calibration results enable determining the laser spot's position on the chip within the global coordinate system of the alignment system if the kinematic mount position is known.

2. Methodology

2.1. Calibration setup

The calibration setup is located on an optical table, where five Gaussian laser beams were established using a laser diode (CPS635 from Thorlabs) coupled with a beam expander (BE10-532 from Thorlabs) and a 3D-printed cover containing five apertures (see Figure 2).

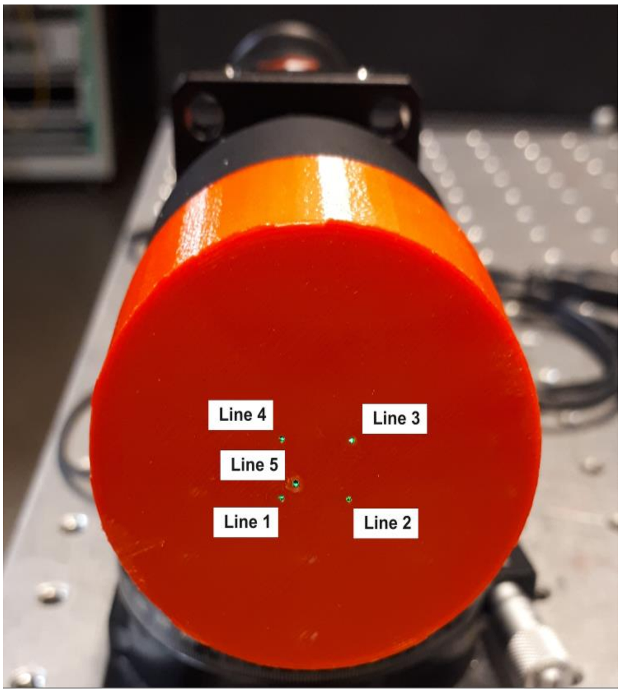

Figure 2. The beam expander cover containing five slits.

The kinematic mounts were placed along the five laser beams. Each kinematic mount was installed with a different rotation. The positions and rotations of the kinematic mounts were carefully arranged to ensure that all five laser spots were visible in the images captured by the camera at each kinematic mount position, see calibration setup in Figure 3. The measurement process was conducted in a metrology laboratory under controlled temperature and humidity conditions.

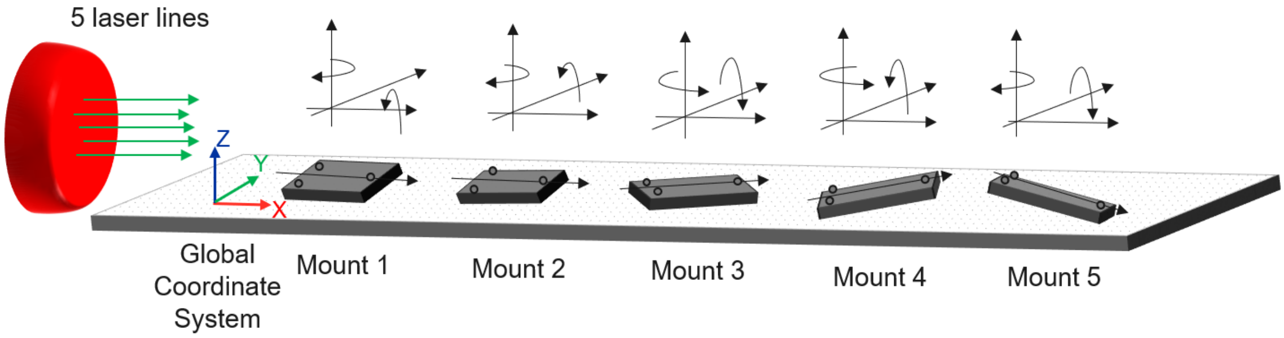

Figure 3. Calibration setup with the line projector and kinematic mounts.

2.3. Measurement procedure

Before capturing photos, the positions of the kinematic mounts within the global coordinate system were determined using a laser tracker. This was achieved by measuring a specially designed artefact, visible in Figure 1, which allows the determination of the 3-ball mount's position. The artefact was previously measured with a CMM, providing sub-micrometre uncertainty for the fiducials and the kinematic mount balls.

The image acquisition was performed at each measurement station across multiple series. During each series, 60 images were captured over two minutes. Three independent series were conducted to assess the repeatability of the fiducialisation. Before each series, the positions of the laser lines were changed to ensure three independent calibrations. A single laser tracker measurement of the artefact in five positions was used across all series. The laser tracker measurement includes two tracker stations.

2.2. Adjustment model

The laser tracker measurements, the CMM artefact data, and the chip acquisition are combined into a single least-squares model to determine the fiducialisation of the chip.

Each observation is described by a functional mathematical model $F(X)$ relating the estimated parameters X and the observations L. All observations are combined into a global estimation problem and result in a (high-dimensional) nonlinear least-squares problem of the form:

$$min\|P_V[F(X) - L]\|^2 \text{ over } X,$$

where P_V is a diagonal matrix containing the weights associated with the expected precisions of each observation.

The estimated parameters describe:

1. The Helmert transformations between the global coordinate system and the kinematic mount coordinate system,
2. The Helmert transformations between the kinematic mount coordinate system and the chip coordinate system,
3. The parameters that define five laser lines in space.

The chip readings of the laser spots can be interpreted as observations of the intersection of the laser line and the chip x/z plane in the chip coordinate system.

The full setup including all the hierarchical coordinate transformations can be conveniently expressed in LGC using the "FRAMES" syntax.

In the mathematical formulation, each of the transformations mount->sensor is described by its own independent set of Helmert parameters. However, per construction, it is known that the relative transformation mount->sensor is identical for all the five chip positions, and we can identify the parameters by including linear constraints in the least-squares estimation. The final nonlinear least square problem then is of the form:

$$min\|P_V[F(X)-L]\|^2 \text{ over } X \text{ such that } C(X)=0,$$

where the function $C(\mathrm{X})$ represents the additional constraints on the transformation parameters. It is solved by a constrained Gauss-Newton method with LGC2.

While the observations from a single sensor mount position would always lead to undetermined parameters, only the combination of the observations from several different sensor positions (differing in position as well as spatial orientation) together with the constraint described above allows the simultaneous estimation of all involved Helmert transformation parameters as well as the laser line parameters.

3. Results

The results of the least-squares calibration are presented in Table 1, which contains the transformation parameters between the kinematic mount and chip coordinate systems. For each of the three series, the table shows the results of the associated least-squares computations as well as the (estimated) standard deviations from the final covariance matrix of the least-square problem.

Table 1 3D transformation parameters (six degrees of freedom) between the chip and kinematic mount coordinate systems, with standard deviations for three acquisition series. The results are presented in the kinematic mount coordinate system.

Parameter	Value		
	Series 1	Series 2	Series 3
TX (m)	0.00730	0.00729	0.00725
TY (m)	-0.05030	-0.05032	-0.05033
TZ (m)	-0.04462	-0.04459	-0.04457
RX (deg)	0.33419	0.06835	0.39976
RY (deg)	359.801	359.892	359.881
RZ (deg)	180.481	180.373	180.577
Parameter	Estimated standard deviation		
TX (mm)	0.06	0.05	0.07
TY (mm)	0.01	0.01	0.01
TZ (mm)	0.08	0.07	0.10
RX (deg)	0.015	0.012	0.017
RY (deg)	0.060	0.052	0.069
RZ (deg)	0.013	0.009	0.015

The virtual corner points of the chip are introduced to ease the interpretation of Table 1. The standard deviations of four corner points (TL, TR, BL, BR) were analysed to evaluate the repeatability of the results across three measurement series, as shown in Table 2.

Table 2.1 The standard deviations of the chip corner points derived from series comparison in the kinematic mount coordinate system.

	std_X (mm)	std_Y (mm)	std_Z (mm)
TL	0.025	0.011	0.022
TR	0.025	0.022	0.013
BL	0.021	0.026	0.022
BR	0.021	0.007	0.013

2.2 The average standard deviations for three series as estimated by the least-squares computation in the kinematic mount coordinate system.

	std_X (mm)	std_Y (mm)	std_Z (mm)
TL	0.060	0.008	0.086
TR	0.060	0.008	0.081
BL	0.059	0.008	0.086
BR	0.059	0.007	0.081

4. Discussion

4.1. Results interpretation

The results in Table 1 confirm the proof of concept for the new geometrical chip calibration method. Differences in the translation parameters between series are within 50 µm, consistent with the estimated standard deviations of up to 100 µm. Each series can be interpreted as an independent acquisition, relying solely on common laser tracker measurements. Interpreting the rotation parameters is challenging because the transformation parameters are interdependent, leading to larger differences between them. These differences exceed their standard deviations.

The raw transformation parameters and their uncertainties may provide limited information due to potential lever-arm effects and correlations between rotation and translation parameters. To better assess the impact of these uncertainties, we examine their effect on the four virtual camera corners in the sensor mount's coordinate system. These standard deviations of corner points do not exceed 30 µm as presented in Table 2.1. The results are similar in all directions as the average standard deviation in the x-direction is 23 µm in the y-direction is 17 µm and in the z-direction is 18 µm.

Table 2.2 presents the estimated standard deviations from the least-squares computation obtained through uncertainty propagation of the transformation parameters to the camera corner coordinates. Although it is not expected that the estimated standard deviations and the standard deviations from the series comparison (table 2.1) match exactly - particularly because the three acquisitions share the same laser tracker observations - both results are of the same order of magnitude. This consistency suggests that the mathematical modelling represents the measurement setup reasonably, but three series do not constitute statistically strong evidence, and future tests should confirm it.

4.2. Calibration limitations and improvements

The unfavourable configuration of the setup limits the precision of the calibration process. Five laser lines were used to increase the number of observations and improve the robustness of the configuration. While it is possible to add more laser lines, interference of light coming from the slits reduces the precision of point detection.

The chip rotation is limited to an angle of 15° due to constraints imposed by the camera housing and the glass protection in front of the chip. Additionally, the inclination is restricted by the kinematic mount, which lacks an attachment screw and relies solely on gravity for positioning.

A limitation of the calibration is the measurement accuracy of the laser tracker, which achieved an accuracy of 17 µm for point 3D positioning. This accuracy can be improved to sub-micrometre levels by measuring the kinematic mounts using a CMM. Prior to this measurement, the kinematic mounts should be placed on an invar plate to ensure the thermal stability of the measured coordinates.

The glass protection, previously mentioned in the context of the chip's maximum rotation, negatively impacts measurement accuracy by potentially deviating the laser’s direction. However, removing this protection might pose risks to the camera's operation. This influence can be assessed and corrected if the plate thickness, wedge angle and position are known.

As shown in Figure 1, the camera rests on a copper support. The size and material of the support are tailored to the intended application of the calibrated chip in the alignment system and cannot be modified. Copper serves as a thermal conductor, dissipating excess heat from the camera, which is especially crucial in a vacuum system where convection-based heat transfer is limited. However, the support's size results in a larger distance between the chip's coordinate system and the kinematic mount's coordinate system than necessary. Reducing this distance could enhance the transformation's accuracy. In addition, the copper support changes dimensions while heated which may also negatively influence the ficucialization.

The camera operates at a temperature of approximately 40°C under normal room conditions, causing thermal expansion and shifts in coordinate values. While the camera was preheated before calibration, its temperature can vary during acquisitions, further limiting calibration accuracy, however, this influence is not considered critical.

The stability of the laser lines is a limiting factor for calibration accuracy. This stability is influenced by the stability of the laser generator over time and atmospheric refraction. The stillness of the generator depends on the inclination of the entire structure and the constancy of its optical parameters. If these elements vary over time, the direction of the laser lines can shift during an average measurement series, which lasts approximately eight minutes. Most variations of the laser source direction are mitigated by the beam expander. The entire setup is mounted on the same honeycomb optical table, further supporting stability. However, even when the line generator is stable, atmospheric refraction can cause deviations, altering the measured laser spot coordinates. Based on the acquisition, this effect is not critical because the standard deviation of the point position on the chip is not larger than 0.5 µm even at the furthest kinematic mount.

5. Conclusion

The proposed calibration method has been validated as an effective tool for determining the reciprocal position of the chip and the kinematic mount. The calibration results are repeatable, with the maximum differences in the chip corner points for independent calibrations being within ±30 µm in the plane of the chip, even though the standard deviation of these points from the least-squares adjustment is three times large. Three series of measurements do not allow for drawing statistically relevant conclusions, therefore more tests are required in the future.

The primary limiting factor is the configuration of the geometrical network, which constrains the results of the fiducialisation. This configuration could be improved by removing the camera housing and using the attachment screws to expose the chip and allow larger rotations of the kinematic mounts.

The *LGC2* software has proven to be a valuable tool for modelling the calibration process and estimating the transformation parameters. The software will be made publicly accessible as an open-source project, enabling broader adoption and further development.

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