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A CRENELLATED-OBJECT-BASED INTRINSIC AND EXTRINSIC CALIBRATION METHOD FOR LASER STRIPE SENSORS INTEGRATION IN ARTICULATED COORDINATE MEASUREMENT ARMS

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Abstract: A technique for intrinsic and extrinsic calibration of a laser stripe sensor (LSS) integrated in a coordinate measurement arm (CMA) is presented in this paper. By means of a single calibration object, a one-step calibration method to obtain both intrinsic (laser plane, CCD sensor and camera geometry) and extrinsic parameters related to CMA main frame has been developed, allowing the integration of LSS and CMA mathematical models. The results obtained in accuracy and repeatability experimental tests show the suitable performance of this method, as well as a great ease of use and a very low time consumption.

Keywords: Laser Stripe Sensor, Coordinate Measurement Arm, Extrinsic and Intrinsic Sensor Calibration, Accuracy Test for non Contact Sensor.

1. INTRODUCTION

The progressive implantation of reverse engineering and digitalization in metrology and quality control has increased the sensors integration needs in instruments traditionally used for dimensional metrology. Precision improvement of equipments over the last years turns them into metrology instruments able to obtain quick and accurate measurements reaching accuracies next to those of a conventional CMM.

LSSs, able to obtain 3D coordinates from the laser line projection on the surface to measure, are based on the triangulation principle. This way, it is possible to reconstruct X,Y,Z coordinates corresponding to the laser line points by combining information provided by the laser plane intersection with the surface to measure, with the camera perspective transformation matrix obtained during the sensor calibration.

The quick integration of this type of 3D sensors in metrology equipment over the last years has been accompanied by a lack of normalization regarding their calibration procedures. Due to this, the manufacturers have developed their own calibration procedures. However, they do not guarantee in a reliable way the accuracy of structured light optical measurement systems because they do not establish general evaluation procedures for the complete systems, due to the great amount of influence parameters over the system final error. The difficulty to mathematically characterize the influence of these parameters on the error in a general way for any LSS has traditionally prevented the development of calibration and later correction methods. Recent works [1] have tried to characterize the error mechanisms for a commercial LSS evidencing that, in optimal measurement conditions, the repeatability obtained in characteristic parameters measured from geometric primitives is better than 10µm. On the other hand, the accuracy obtained with a LSS able to obtain 60.000 pt/sec, when measuring gauge objects or compared with those of a CMM, goes from tens of micrometers up to 0.5 mm. According to the mentioned studies, low values of repeatability indicate that it is necessary to establish effective error correction models to take advantage of the metrological characteristics of this kind of devices.

Another conclusion obtained by several authors [2] is that the main influence in the error of a LSS is the determination procedure to establish the relationship between the sensor frame and the global frame of its support. Alternatively, the LSS-CMA system calibration is different from the calibration of the sensor itself. This calibration, called intrinsic calibration, pursues to obtain the laser plane equation and to define the sensor reference frame, as well as to fix the relationship between screen coordinates u,v and X,Y,Z coordinates in the sensor frame. In addition, depending on the calibration model chosen, it is possible to describe the influence of other parameters like lens distortion. On the other hand, the extrinsic calibration obtains the relationship between the sensor frame, defined during its intrinsic calibration, and the global reference frame of the support of the sensor for digitalization, in which the digitized points will be obtained. Previous works have studied the intrinsic calibration of this type of sensors [3] and the influence of the calibration process in the final error, as well as the development of optimization procedures for intrinsic parameters. On the other hand, several authors have studied the way to solve the intrinsic and extrinsic calibration simultaneously [4], by means of techniques difficult to be applied outside the laboratory.

Several possible assembly configurations using LSSs are been used in industry nowadays. Some of them use a CMM, a robot or a CMA and others are assembled on specific high precision positioning systems or static structures under which the geometries to be digitized displace. The way to determine the relationship between the fixed frame (LSS or support) and the moving one will have a great influence in the final accuracy of the system.

Thereby, these systems demand a simple and reliable procedure to obtain the geometric relationships between the LSS frame, determined during its calibration, and the world coordinate system of its support, for example a CMM. Sensor manufacturers carry out the extrinsic calibration respect to a reference system on the sensor, what makes necessary to transfer this extrinsic calibration to the LSS support. Several works try to solve this problem by scanning reference spheres in multiple spatial positions or by scanning the same sphere from three different sensor scanning paths in the same axis with a predefined offset between scans. Recent studies [5, 6] have successfully solved the extrinsic calibration problem of LSS mounted in CMM by establishing conjugated point pairs in both reference systems, taking advantage of the CMM ability to move in a single axis.

When the sensor is mounted on a manually operated CMA, it is impossible to apply these procedures without aid of expensive instruments, because it is not possible to move only in a single axis of its reference system during the digitalization of points to obtain the conjugated pairs. Hence, it is necessary to raise another method of extrinsic calibration. This is the reason why LSS manufacturers carry out LSS-contact probe set intrinsic and extrinsic calibration mounting it on a CMM (Fig. 1). After that, the extrinsic calibration is reduced to obtain, by the mentioned procedures, the geometric relationship between the LSS reference system and the contact probe reference system. Later, the complete set is mounted in a CMA, integrating the sensor in its mathematical model through its well-known relation with the contact probe.

Fig. 1. LSS–contact probe set sample for intrinsic and extrinsic calibration on CMM

2. PURPOSE

The aim of this paper is to describe a complete calibration method of a LSS integrated in a CMA. The method has been developed to carry out, in a single operation, intrinsic and extrinsic calibration, without need of using previous calibration methods in CMM. Calibration is carried out by obtaining conjugated pairs of points in the sensor and the CMA systems of reference, using a gauge object for this purpose and also for making the LSS intrinsic calibration. Thereby, in a single operation, a simple, cheap and accurate method is obtained to solve the system model and to calculate the transformation matrix that relates sensor frame and global reference frame of the CMA for each digitalization position. Sensor calibration algorithm is presented, as well as the procedure to identify the conjugated pairs of points, required to integrate both mathematical models.

3. CALIBRATION METHOD

3.1. Coordinate measurement arms

CMAs, also named portable CMMs, are contact measurement systems manually operated and made up of several degrees of freedom (dof) joints linked by bars, offering a total of six or seven dof in order to obtain a portable measuring equipment with great versatility (Fig 2). The mathematical models of CMAs are based on the successive determination of transformation matrices among each joint associated frame. Coming from Denavit-Hartenberg (D-H) basic model, several models that allow, by means of new geometric parameters and optimization or final effector positioning error characterization, have been developed to correct the CMA manufacture and assembly imperfections [7]. For the implementation of this LSS-CMA calibration method, basic D-H model has been used to describe the kinematics of any commercial CMA. This model, for a 6 degrees of freedom CMA, can be expressed as follows:

$$\overline{X}_{CMA} = A_1 A_2 A_3 A_4 A_5 A_6 \overline{X}_{Probe} \qquad (1)$$

where A_i is an homogenous transformation 4x4 matrix that obtains the coordinates of a point in a frame coming from same point coordinates in the previous joint frame, X_{probe} are the spherical tip probe coordinates related to the last CMA joint and X_{CMA} are the probe sphere coordinates obtained in the global CMA frame.

$$A_i = \begin{pmatrix} R_i & T_i \\ 0 & 1 \end{pmatrix} \qquad \overline{X}_{i-1} = A_i \cdot \overline{X}_i \qquad (2)$$

In Eq. 2 R_i is a 3x3 rotation matrix with the unitary vectors components of i frame expressed in i-1 frame coordinates, and T_i is a 3x1 translation vector from the origin of frame i to i-1. Other expressions for the A_i matrices exist, based in Euler angles, witch reduce the number of necessary parameters to characterize the transformation, although its general form is the shown in Eq. 2. In order to absorb manufacture and assembly, elastics, thermal and electronic components errors, with regard to the nominal mathematical model, it is frequent to introduce an intermediate transformation matrix that changes coordinates expressed in real frame, located in another position and orientation, into the nominal frame for each joint, obtaining the model:

$$\overline{X}_{CMA} = A_1 E_1 A_2 E_2 A_3 E_3 A_4 E_4 A_5 E_5 A_6 E_6 \overline{X}_{Probe} \qquad (3)$$

where E_i is a 4x4 homogenous error matrix with the Euler angles and the necessary translation to transform coordinates from the real frame to the nominal one of each joint. Basic D-H model (Eq. 1) characterise each joint and CMA section with four geometric parameters, a_i, α_i, d_i and θ_i, allowing to obtain A_i matrix for each pair of reference frames. Other mathematical models for CMAs based in this model exist, which generalize their use for robot arms with combinations of prismatic and revolving joints adding more parameters to describe the kinematics, solving indetermination problems present in certain robot arm configurations.

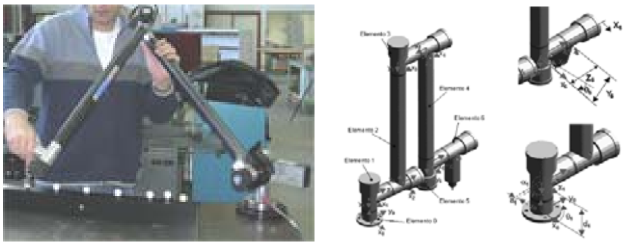

Fig. 2. Six d.o.f. coordinate measurement arm. Geometric parameters and articulation frames.

In this work, as mentioned above, basic D-H model is used because perfectly describes the kinematics of any commercial CMA. In any case, the presented model is easily generalizeable to other CMA or robot mathematical models. Inadequate geometric parameters, will cause measurement errors in probe center coordinates. Thereby it is necessary to previously and separately make a correct determination of the CMA geometric parameters to avoid the propagation of errors due to a bad CMA characterization through the digitized points. Many geometric parameters calculation and optimization methods have been developed during the past years allowing CMAs measurement error minimization.

3.2 Calibration procedure

CMA-LSS integration demands the determination of the geometric relationships between LSS frame and the CMA last joint frame. Thus, the extrinsic calibration procedure of a LSS mounted on a CMA consists of determininig the sensor frame origin coordinates and its direction related to the CMA last joint frame. Thereby, the laser line point coordinates are obtained in this system and, therefore, also respect to CMA global frame (Eq. 4).

$$\overline{X}_{CMA} = A_1 A_2 A_3 A_4 A_5 A_6 M_{LSS->6} \overline{X}_{LSS} \tag{4}$$

Next step consist of obtaining conjugated pairs of measured points in both LSS frame and CMA global frame to calculate a $M_{LSS->CMA}$ matrix that relates both elements. Due to the impossibility to digitize gauge objects before establishing the relation of frames, it is necessary to take points with known coordinates in both frames. Once made the LSS intrinsic calibration on a CMM, when the LSS is linked to the arm, due to the point reconstruction process nature in LSS model, only points of the captured laser line are known in LSS frame, from which the coordinates in CMA global frame cannot be obtained. Due to that, it is required to make LSS intrinsic calibration once mounted on CMA, when the camera calibration object point coordinates can be known in LSS frame.

Thus, first of all, a crenellated calibration object, that materializes points with known coordinates in a frame local to the object, is measured by contact with the CMA to align a reference frame attached to the calibration object and calculate a transformation matrix $M_{CAL->CMA}$ to know the calibration object points in CMA global frame (Fig. 3). Once known the calibration object points coordinates in the CMA global reference frame, an image of the calibration

Fig. 3. Conjugated point pairs identification to obtain $M_{LSS->CMA}$ transformation matrix.

object is captured with the LSS in certain CMA position. Based on pin-hole camera model, LSS intrinsic calibration procedure is made with the captured image and the camera and laser plane parameters are calculated by Faugeras method [8]. Now, not only the laser line points but also the calibration object points coordinates are known in LSS frame. At this point two options exist. If, during the intrinsic calibration (Fig. 3), the LSS reference system have been defined in a different position to the local reference frame of calibration object, it is necessary to obtain a transformation matrix $M_{LSS->CMA}$ by least squares approximation (Eq. 5) using object point coordinates known in both reference systems.

$$\overline{X}_{CMA} = M_{LSS->CMA} \overline{X}_{LSS} \tag{5}$$

On the other hand, it is possible to define intrinsic calibration procedure to make coincident, in the calibration position, the LSS reference frame with the local frame of the calibration object. Thus, the process is simplified avoiding $M_{LSS->CMA}$ matrix least squares calculation, since, in this case, this matrix will be the same as the one obtained in calibration object contact measurement.

$$M_{LSS->CMA} = M_{CAL->CMA} \tag{6}$$

With Eqs. 5 and 6, laser line points can now be obtained in CMA global frame. A new transformation matrix is necessary to express these points in the last CMA joint frame. Matrix that makes this link will be $M_{CMA->6}$ that will coincide with inverse matrix of A1 to A6 matrices product (Eq.1) corresponding to CMA position during calibration image capture. Thereby, it is possible to calculate the searched matrix, which will obtain laser line point coordinates related to last CMA joint frame (Eq. 7).

$$\overline{X}_{6} = (A_1 ... A_6)^{-1} M_{LSS->CMA} \overline{X}_{LSS} = $$

$$= M_{CMA->6(intrinsic\_cal.\_position)} M_{LSS->CMA} \overline{X}_{LSS} \tag{7}$$

$$M_{LSSprobe} = M_{CMA->6(intrinsic\_cal.\_position)} M_{LSS->CMA} \tag{8}$$

In Eq. 8, a transformation matrix between the LSS and the last CMA joint frame independent of the CMA position is obtained, since both systems have solidary movement. If the position of the sensor according to the calibration object remains constant, this matrix will be the same independently of the CMA position at the moment of calibration image capture, occurring small variations due to the error introduced by CMA kinematic model geometric parameters. Finally, it will be necessary to apply CMA model with present position j geometric parameters values (Eq. 9) to obtain the captured laser line coordinates in any CMA position.

$$\overline{X}_{CMA} = (M_{6->CMA})_j \, M_{LSSprobe} \, \overline{X}_{LSS} \qquad (9)$$

Matrix $M_{LSSProbe}$, obtained in Eq. 8, has been called “probe matrix”, since integration of both mathematical models produces one more link in the CMA kinematic chain, replacing the contact probe sphere center by laser line points related to the LSS own reference frame. Fig. 3 shows the process to align, by contact measurements, the CMA global frame with the calibration object frame and Fig. 4 resumes the process showing all frames and transformations implicated.

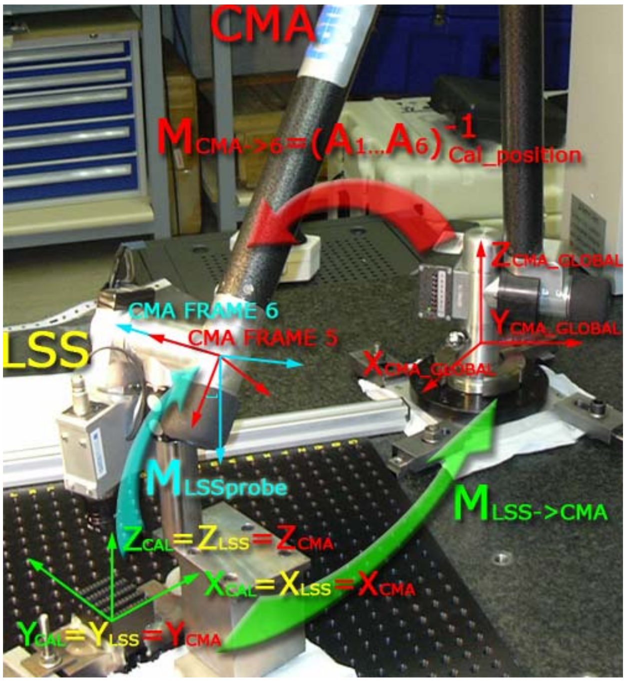

Fig. 4. Frames and transformations in calibration pose.

4. TESTS AND RESULTS

In order to analyze the accuracy and repeatability of the procedure, several calibration tests have been carried out using a FARO CMA (Sterling Series) with a measuring range of 3 m and 250 µm of maximum error. A commercial LSS (DATAPIXEL Optiscan H-1040-L) has been linked to the CMA, able to obtain 30.000 pt/sec with nominal repeatability, according to manufacturer specifications, of 10µm. Previous studies on this sensor mounted in a CMM [1] show that, in optimal capture conditions, is able to obtain this level of repeatability in the nominal range, with accuracies around 100µm measuring gauge planes and spheres.

First of all, 10 different calibrations have been made, obtaining 10 $M_{LSSProbe}$ matrices in different CMA orientations, remaining fixed the position of the calibration object. Results do not show definitive values of the calibration process repeatability, since important variations in matrices terms are observed, mainly in the translation terms, due to the impossibility to fix the relative position between the LSS and the calibration object. Due to the fact that the LSS reference frame is fixed in the calibration object local frame during its intrinsic calibration, differences between calibrations are expected, since the relative position between this reference system and the last CMA joint frame changes for each calibration. Thereby, to analyze calibration influence over captured points accuracy and repeatability, it is necessary to define a method that allows to reconstruct the same captured points with the 10 different calibrations made. Because of that, an algorithm has been developed to reconstruct points in CMA coordinates from the known u,v screen coordinates of the captured laser line points, the laser plane equation and the perspective transformation matrix obtained in each intrinsic calibration.

As a repeatability analysis of the calibration procedure, a gauge plane has been digitized obtaining 10 different point clouds for the same plane. For each one of these clouds, the u,v coordinates of the laser line points have been stored, in addition to the CMA joint reference frames position for each captured line, so that the laser line points expressed in CMA global reference frame can be reconstructed in accordance with the chosen calibration. Therefore, once the clouds are reconstructed, 10 clouds of points for each calibration are obtained. Thus, a total of 100 clouds are calculated, with information of a same cloud of points reconstructed with 10 different calibrations. Since the mentioned studies demonstrate the high repeatability of the intrinsic calibration procedure, the results obtained for the digitized plane, will show the influence of the extrinsic calibration in the final result.

A plane has been chosen as gauge geometric primitive in the first test. The nominal value for the plane equation has been obtained like the average result from 10 CMA contact measurements of the plane (Fig. 5) with 10 points each, to absorb, as far as possible, the errors derived from the CMA kinematic model parameters.

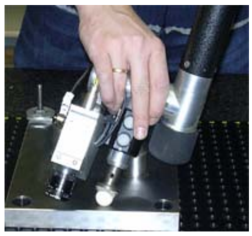

Fig. 5. Gauge plane contact measurement.

After that, 10 clouds of points have been obtained digitalizing the plane, storing described parameters for its later reconstruction in CMA global coordinates (Fig. 6).

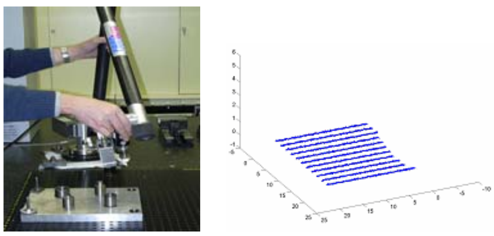

Fig. 6. Gauge plane digitalization.

Once reconstructed clouds of points, digitized plane equation for each one has been determined by least squares estimation, including segmentation and point filtration techniques based on the standard deviation of point distances to the calculated plane.

Two error parameters have been chosen. Firstly, the angle between the nominal and the calculated plane normals, and finally the difference in Z coordinate of the central point of the cloud projected on the nominal and the calculated plane. Eq. 10 and 11 show the error expressions for cloud i corresponding to calibration j for the normalized equation values of nominal and measured planes.

$$\varepsilon a_{ij} = a\cos(A_N \cdot A_{ij} + B_N \cdot B_{ij} + C_N \cdot C_{ij}) \quad (10)$$

$$\varepsilon z_{ij} = Z_N - Z_{ij} \quad (11)$$

$$Zij = \frac{-A_{ij} \cdot X_C - B_{ij} \cdot Y_C - D_{ij}}{C_{ij}} \quad (12)$$

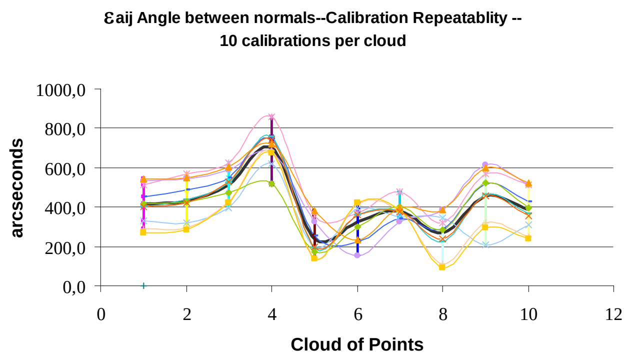

Fig. 7. Angle between normals. System repeatability and calibration process influence.

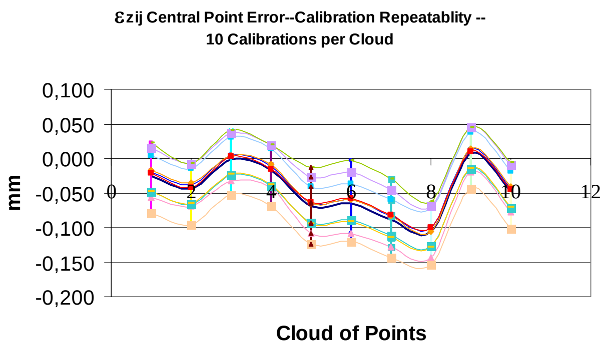

Fig. 8. Projected central point error. System repeatability and calibration process influence.

Fig. 7 shows the results obtained for the angle between normals. It is possible to see two effects in this figure. Firstly, the error obtained for 10 clouds with each calibration (curves along x axis) is represented. Each one of these curves represents the repeatability of the process of capture of points with a single calibration, reason why the variability and the error in this case, are referable to the measurement system. The maximum value for all calibrations, obtained for this value of system repeatability, is around 500 arcsecs, attributable to the repeatability of the CMA-LSS system for a certain calibration. Secondly, for each cloud of points, the range of the values obtained with each calibration is represented, showing a mean range for the angle between normals due to the calibration procedure of around 230 arcsecs. Thus, it is observed an important influence of the calibration process in the results, although, in this point, it is not possible to isolate this influence from other error sources due to the process of capture itself, like the lack of squareness of the laser plane respect to the digitized surface, the variations in capturing distance during the digitalization, or the CMA repeatability.

With the aim to try to isolate the influence of the calibration process, Fig. 9 is presented. In this case, the mean range of the error for 10 clouds of points for each calibration has been calculated, obtaining, as mentioned above, values around 500 arcsecs for each one with low standard deviations. If the variations produced in this range when reconstructing the clouds with different calibrations are calculated, a variation of the average repeatability values within the range of ±30 arcsecs around the mean repeatability value of the system is observed, directly attributable to the calibration process.

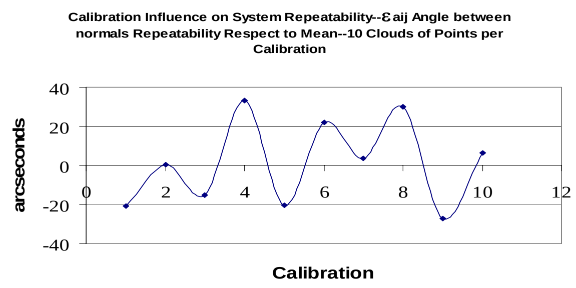

Fig. 9. Calibration influence on system repeatability. Angle between normals mean repeatability.

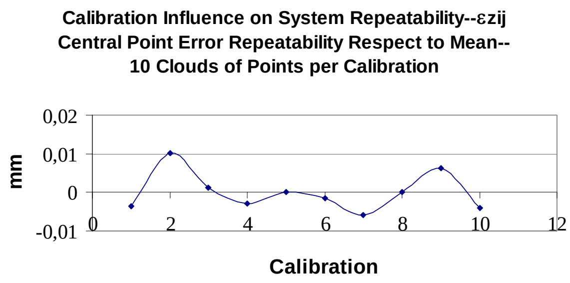

Fig. 10. Calibration influence on system repeatability. Projected central point error mean repeatability.

Figs. 8 and 10 represent the effect of the calibration process in Z error. As in the case of angle between normals, repeatability values for Z within the same calibration around 110µm are observed and they are attributable to the system repeatability (Fig. 8). On the other hand, an important influence of calibration is appraised again in the system accuracy, introducing variations of 100µm in Z error. Fig. 8 shows the influence of the calibration process in the average system repeatability, introducing maximum variations within range of ±10µm.

Once analyzed the repeatability, to make an estimation of the complete system accuracy, a reference ceramic sphere has been digitized 5 times reconstructing the clouds of points with the calibration next to the average values of error obtained in angle between normals and Z. To emphasize the influence of the points capture strategy, the sphere has been digitized 5 times orienting the laser plane perpendicular to the surface, and other 5 times with an orientation of the LSS similar to the one used for its calibration. The results (Fig. 11) show appreciable differences in the accuracy of the system based on the direction of the laser plane.

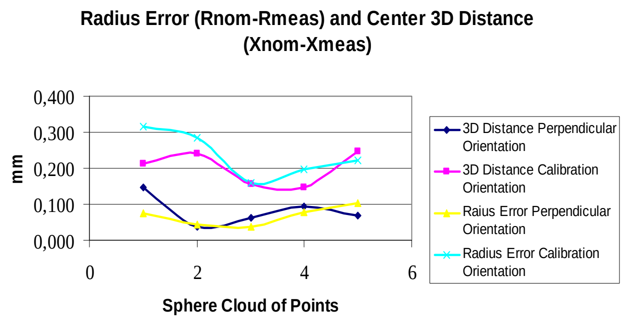

Fig. 11. Accuracy estimation of the whole system. Radius and center distance errors digitizing a reference sphere.

Best results are obtained for laser perpendicular orientation to the sphere surface, showing accuracies around 50µm in radius error ($R_{NOMINAL}$-$R_{MEASURED}$) and 90µm in distance between centers error. In the previous graph it must be considered that a ceramic sphere has been used as reference object, being partially translucent and producing laser penetration into its surface, resulting in a measured radius smaller than the nominal one. The influence of the capture conditions is significant, mainly considering the difficulty to keep constant the capture conditions in a manually operated system of measurement.

5. CONCLUSIONS

This paper presents a new intrinsic and extrinsic LSS-CMA calibration method allowing to make the calibration procedure in a single step with the LSS already mounted in CMA, with no need to characterize LSS+Contact probe set geometry by means of calibration methods on CMM. Thereby, a simple and cheap calibration method for the final user, required for any portable measurement equipment, is obtained. By means of the use of a crenellated reference object that materializes points in two different planes regarding to a local reference frame, it is possible to obtain the equation of the sensor laser plane, its perspective transformation matrix and the necessary conjugated pairs of points in LSS frame and CMA frame for the extrinsic calibration in a single operation. The experimental results show the repeatability of the calibration process by means of digitalization of gauge primitives, with suitable accuracies for CMA-LSS digitalization systems. On the other hand, it is necessary to emphasize the lack of standardized calibration procedures for this type of systems. Without these procedures, it is impossible to define, in a general way, the metrological characteristics of this type of equipment as much in tasks of inspection as in tasks of reverse engineering.

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