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T. Pyrog, postgraduate student, A. Pyrog
(National Aviation University, Ukraine)

CALIBRATION TECHNIQUE OF LASER TRIANGULATION SENSORS FOR INTEGRATION IN ROBOT ARMS

Coordinate measuring machines (CMM) are essential for quality assurance and production control in modern manufacturing. Due to the necessity of assuring traceability during the use of CMM, interim checks with calibrated objects carried out periodically. The paper describes a technology for calibration of a laser triangulation sensor which intergraded in articulated arm in coordinate measuring machine.

1. Introduction. Laser triangulation sensors (LTSs), able to obtain 3D coordinates from the projection of laser line onto the surface to be measured, are based on the triangulation principle and mainly composed of camera and laser diode with a cylindrical lens capable of projecting a plane. 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 be measured and the camera perspective transformation matrix obtained during the sensor calibration.

The rapid integration of this type of 3D sensor in metrology equipment over recent years has been accompanied by a lack of standardization regarding their calibration procedures. For this reason different manufacturers have developed their own calibration procedures. In particular, LTSs are nowadays the most commonly used non-contact sensors in traditional dimensional metrology equipment such as CMMs or articulated arm coordinate measuring machine (AACMMs).

This is due to their versatility and the fact that they are one of the most accurate structured light contactless measurement sensors, providing suitable accuracy values for most reverse engineering applications although, in general, these are not sufficient for metrological inspection tasks.

AACMM applications with integrated laser sensors are, nowadays, mainly focused on the automotive, aeronautics and moulds sectors, and applications related to heritage conservation and general measurements of industrial components.

2. LTS Calibration. The calibration method presented in this section performs the intrinsic and extrinsic calibration of the sensor in a single step, so it is not necessary to have the LTS previously calibrated. Furthermore, it is based on the capture of an image of a gauge object in a single AACMM position, so the error influence of the arm due to the error made during the scan paths is avoided, absorbing only the measurement error in the contact measurement procedure of the gauge object and the error in the AACMM capture position of the image for calibration.

In the current integration procedures based on error optimization over digitalized data, once the LTS intrinsic calibration has been done on a CMM, due to the point reconstruction process nature used in the LTS model, only points belonging to the captured laser line are known in the LTS frame when the LTS is linked to the arm. Thus, the coordinates of these points in the AACMM global frame cannot be obtained in this situation. In order to avoid approximate optimization procedures so as to determine the sensor position and orientation in AACMM coordinate system, it is necessary to do the LTS intrinsic calibration once it is already mounted onto the AACMM, when the camera gauge object point coordinates can be known in the LTS frame.

Equation 1 represents the equation of a straight line in the space which connects the point in the 3D global reference system with the point in the image.

$$\begin{Bmatrix} m_{11} \cdot X_W + m_{12} \cdot Y_W + m_{13} \cdot Z_W - m_{31} \cdot u \cdot X_W - m_{32} \cdot u \cdot Y_W - m_{33} \cdot u \cdot Z_W - u \cdot m_{34} + m_{14} = 0 \\ m_{21} \cdot X_W + m_{22} \cdot Y_W + m_{23} \cdot Z_W - m_{31} \cdot u \cdot X_W - m_{32} \cdot u \cdot Y_W - m_{33} \cdot u \cdot Z_W - u \cdot m_{34} + m_{24} = 0 \end{Bmatrix} \quad (1)$$

Equation (1) defines a system of two equations with three variables. This is the reason why more information is necessary to obtain the required coordinates. Once the camera is modelled, its later calibration will provide the values of the m_{ij} coefficients of the perspective transformation matrix. LTS calibration implies the determination of the *intrinsic and extrinsic parameters* of the camera, and therefore the terms of the perspective transformation matrix of Equation (1) expressed in its coordinate system. The terms of the laser plane equation in this coordinate system, shown in Equation (1), are also obtained during LTS calibration.

The laser plane is modelled by the general equation of a plane expressed in the global coordinate system:

$$cAX_W + cBY_W + cCZ_W + cD = 0 \tag{2}$$

The laser plane contributes with the additional information necessary to complete the equation of the straight line of the camera model and to achieve a system of three equations with three variables for each identified point, so that their 3D global coordinates can be extracted from their 2D screen coordinates u, v. (Figure 1).

Image of the calibration object is captured with the LTS in a single AACMM posture. This image, as can be appreciated in Figure 2, must contain the points of the gauge object and the laser line corresponding to the intersection of the LTS plane with the object. From the captured image it is possible to determine the image coordinates u, v in pixels, corresponding to the centre of each one of the object points by means of centroid calculation.

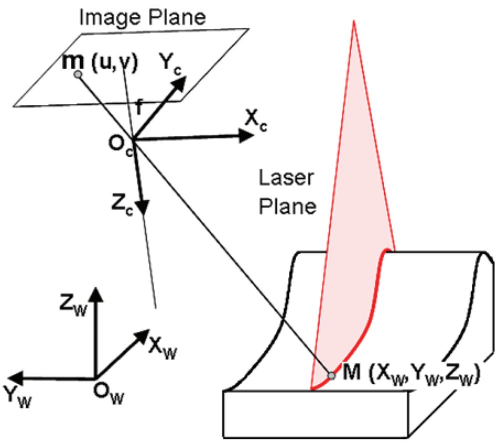

Figure 1. The global coordinates of a point M in the laser line image are computed from camera model and laser plane equation.

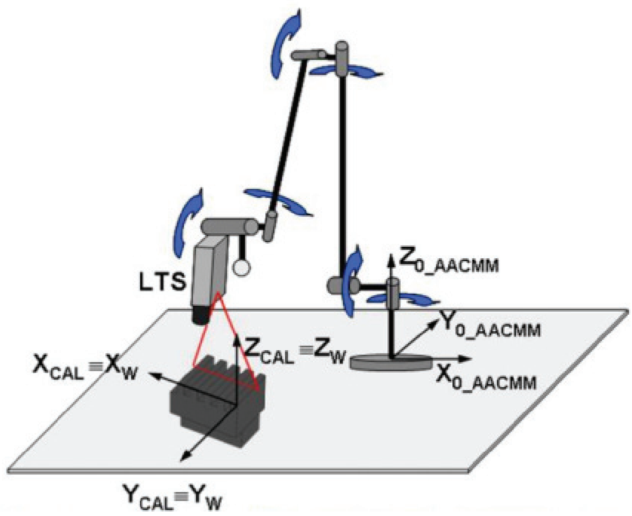

Figure 2. Image capture for LTS intrinsic calibration in AACMM calibration position.

The perspective transformation matrix being homogenous, the solution is modified by a scale factor, reason why the condition $m_{34} = 1$ is imposed, considering that this term is not null since t_z contains the term corresponding to the camera coordinate system translation to the LTS global coordinate system. It is possible to obtain the subsequent scale factor to be applied on the obtained matrix forcing the vector formed by the three first components of the last row of the matrix to be unitary. This scale factor will match with the translation t_z. In these conditions it is possible to write in matrix form the equations obtained according to Equation (1) for each considered calibration point, obtaining a system of equations in the form of Equation (3):

$$Am = 0, \tag{3}$$

where,

$$A = \begin{bmatrix} X_{Wi} & Y_{Wi} & Z_{Wi} & 1 & 0 & 0 & 0 & 0 & -u_i X_{Wi} & -u_i Y_{Wi} & -u_i Z_{Wi} & -u_i \\ 0 & 0 & 0 & 0 & X_{Wi} & Y_{Wi} & Y_{Wi} & 1 & -v_i X_{Wi} & -v_i Y_{Wi} & -v_i Z_{Wi} & -v_i \\ X_{Wi+1} & Y_{Wi+1} & Z_{Wi+1} & 1 & 0 & 0 & 0 & 0 & -u_{i+1} X_{Wi+1} & -u_{i+1} Y_{Wi+1} & -u_{i+1} Z_{Wi+1} & -u_{i+1} \\ 0 & 0 & 0 & 0 & X_{Wi+1} & Y_{Wi+1} & Z_{Wi+1} & 1 & -v_{i+1} X_{Wi+1} & -v_{i+1} Y_{Wi+1} & -v_{i+1} Z_{Wi+1} & -u_{i+1} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ X_{Wn} & Y_{Wn} & Z_{Wn} & 1 & 0 & 0 & 0 & 0 & -u_n X_{Wn} & -u_n Y_{Wn} & -u_n Z_{Wn} & -u_n \\ 0 & 0 & 0 & 0 & X_{Wn} & Y_{Wn} & Z_{Wn} & 1 & -v_n X_{Wn} & -v_n Y_{Wn} & -v_n Z_{Wn} & -v_n \end{bmatrix} \quad (4)$$

and

$$m = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} & m_{21} & m_{22} & m_{23} & m_{24} & m_{31} & m_{32} & m_{33} & m_{34} \end{bmatrix}^T \quad (5)$$

LTS calibration, in addition to giving the camera intrinsic parameters, defines the position and orientation of the sensor global coordinate system. In this way, by means of this calibration, the sensor global coordinate system is defined coincident with the gauge object local coordinate system in which are known the 3D point coordinates.

Finally, in the subsequent LTS operation, the information provided by the laser plane complements Equation (1) and allows the reconstruction of the 3D global coordinate system by means of Equation (6) applied to each point, from the screen coordinates u, v after the identification of the points in the image:

$$\begin{bmatrix} m_{11} - m_{13} \cdot u & m_{12} - m_{32} \cdot u & m_{13} - m_{33} \cdot u \\ m_{21} - m_{31} \cdot v & m_{22} - m_{32} \cdot v & m_{23} - m_{33} \cdot v \\ cA & cB & cC \end{bmatrix} \cdot \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = \begin{bmatrix} -u + m_{14} \\ -v + m_{24} \\ cD \end{bmatrix} \quad (6)$$

It is necessary to note that the sensor calibration has been shown without considering distortion effects on the reconstructed points. These effects are very low in the modelled sensor because the capture distance to the surface only allows the capture of points in the range of ±5 mm around the central line of the captured image, where the distortion effects are minimum. In order to verify distortion effects on the reconstructed points, the calculation of the screen coordinates corresponding to the gauge object points after the calibration has been made, obtaining mean values of 0.224 pixels in maximum error for the u coordinate and 0.233 for the v coordinate in several calibration tests.

2. AACMM-LTS extrinsic calibration. Once the sensor calibration from the captured image has been done, not only the laser line points but also the calibration object points coordinates are known in the LTS global frame. This calibration defines the sensor global reference system that matches the gauge object local coordinate system for the position of image capture. In this way, the matrix that relates the sensor global coordinate system to the AACMM global coordinate system for the AACMM capture image position is the transformation matrix obtained by contact measurement of the gauge object in Equation (3). Rewriting this equation, the expression of Equation (7) is obtained, valid only for the AACMM and LTS position and orientation used in the image capture:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{0\_AACMM} = {}^{AACMM}M_{W\_LST} \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{W\_LTS} \quad (7)$$

where ${}^{AACMM}M_{W\_LST} = {}^{AACMM}M_{CAL}$.

With Equation (7), laser line points can now be obtained in the AACMM global frame for the calibration position. The matrix that makes this link is ${}^{6\_AACMM}M_{0\_AACMM}$ that will coincide with the inverse matrix of the product of matrices A_1 to A_6 of Equation (3) corresponding to the AACMM position during calibration image capture. Thereby, it is possible to calculate the desired homogeneous transformation matrix, which will obtain laser line point coordinates related to the last AACMM joint frame for the calibration position:

$$\begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{6\_AACMM} = ({}^0T_6)^{-1}_{Calibration\_pos} \cdot ({}^{AACMM}M_{W\_LST})_{Calibration\_pos} \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{W\_LTS} \quad (8)$$

With this, it is possible to define the desired matrix by means of Equation (8). This matrix contains the sensor extrinsic parameters that determine the position and orientation of the sensor global coordinate system with respect to the last coordinate system of the kinematics chain of the arm.

Finally, it will be necessary to apply the AACMM model with the current position j geometric parameter values to obtain the captured laser line coordinates in any AACMM position, as shown in Equation (9):

$$\begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{0\_AACMM} = ({}^0T_6)_j \cdot M_{LTS\_\mathrm{Pr}obe} \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}_{W\_LTS} \quad (9)$$

where the vector $\begin{bmatrix} x_i & y_i & z_i & 1 \end{bmatrix}^T_{W\_LTS} = \begin{bmatrix} X_{Wi} & Y_{Wi} & Z_{Wi} & 1 \end{bmatrix}^T$ is calculated in Equation (6) for each identified point of the laser line in the image. Matrix $M_{LTS\_\mathrm{Pr}obe}$, obtained in Equation (10), has been called the “probe matrix”, since integration of both mathematical models produces one more link in the AACMM kinematics chain, replacing the contact probe sphere centre by laser line points related to the LTS global reference frame.

Conclusions

This paper presents an intrinsic and extrinsic LTS-AACMM calibration method, the calibration procedure being performed in a single step with the LTS already mounted in the AACMM, with no need to previously characterize the LTS-Contact probe set geometry by means of calibration methods on CMM. This method is based on the continuous capture of arm positions by directly probing the centre of the spheres of a gauge ball bar by way of a self-centring kinematics coupling probe. Oppositely, current methods are based on the capture of identification data probing surface points of geometrical primitives of different gauge objects.

References

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