Calibrating the geometric position of a plane laser-beam vision-sensor in a measuring system for tridimensional shapes

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The paper describes the calibration process for a shape acquisition system made of an optical 3D sensor mounted on a mobile set, capable of delivering the absolute coordinates of a cloud of points that are representative of an object's shape in an absolute reference system.

The calibration process aims at establishing the global transfer function between the ndata given by the device and the tridimensional values that correspond to the workpiece's measured dimensions in an absolute reference defined by the geometry of the mobile set holding the sensor.

PRESENTATION OF THE SENSOR TECHNOLOGY

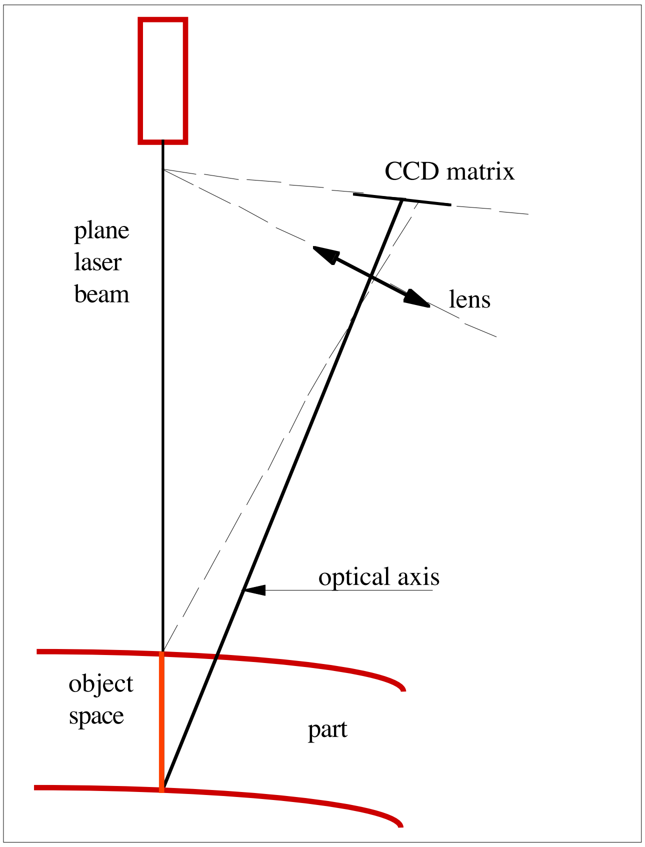

fig.1 : Triangulation principle of optical 3D sensor

The acquisition system studied is composed of an optical sensor mounted at the end of a manipulating 5-axes device built with a linear measuring 3-axes tool and a 2 rotative indexed axes swivelling head.

The sensor is composed of a plane laser-beam source and of a CCD matrix camera that will analyze the picture formed by the laser beam on the studied object.

The acquisistion process uses the triangulation principle.

This sensor technique is based upon the emission of a very thin foliated laser beam whose width allows to cover a very large part of the object to analyse; a camera visualizes this plane under incidence, with a fixed triangulation angle, and acquires the line of impact of the laser beam on the part whose coordinates are measured on the camera's CCD matrix.[3], [1].

Camera set The position of the CCD matrix is defined by the relative position between the lens and the object-space as defined by the laser-plane. As the object-plane is not orthogonal to the optical axis, the CCD matrix has to be tilted in relation with it, so that it fits the image-plane. The image of an object-point is thus a point belonging to the CCD matrix, in relation with the lens [3].

THE ISSUE

The calibration process is the main element of an acquisition system. Indeed, the global transfer function is established at that stage. It permits the connection of the bidimensional data given by the camera picture and the tridimensional data of the points acquired on the part in an absolute reference system.

This process thus conditions the accuracy of the acquisition.

Most calibration processes have, up to now, connected the CCD camera's raw data and the real data of the part's points thanks to a prior knowledge of the lighting system's geometry in relation with the video system. It takes into account the prior setting of the parallax between a plane modeling of the laser beam and the axes of the absolute reference system as well as the prior setting of the camera's lens .

However, the positions of the elements of the sensor cannot always be accurately set. Moreover, to obtain the quality of the optical system that will allow for the making of the plane laser-beam and the acquisition by the camera, the modeling of the acquisition process has to take its defects into consideration : lens geometric defects, distorsions, lens positioning defects [3], [2], [4].

Calibration is the set of operations that will, in specified conditions, establish the relationship between the values given by the device and the known values corresponding to a measured size (NF X 07-001 6 13).

The definition of the calibration process thus entails the study of the geometry of the reference element that will allow for the assessment of the parameters of the transfer function between the data given by the sensor and the real coordinates of the part's points. The transfer function is defined by the modeling of the acquisition system [2].

MODELING THE ACQUISITION SYSTEM

Definition of the varied reference points Modeling requires the definition of 5 reference points attached to the different elements of the acquisition system.

Object reference: Ro

It is the 3D reference point of the real world, whose axes directions are defined by the measuring tool's axes and the origin by the reference element Oo. The coordinates of a point in this reference system are noted (Xo, Yo, Zo).

Machine reference: Rm

It is the 3D reference connected to the measuring tool whose origin is Om.

Sensor reference: Rcap

It is the 2D reference point whose two axes x and y are parallel to the lines and colums of the CCD matrix. The coordinates of a point in this reference system are noted (l,c).

Camera reference: Rc.

It is the 3D reference point whose origin is the center of perpective projection, whose axis z is merged into the optical axis, and whose axes x and y are the projection of the lines and columns of the CDD matrix in the plane orthogonal to the axis z. The coordinates of a point in this reference system are noted (Xc, Yc, Zc).

Laser reference: Rla

It is the 3D reference point whose origin is the intersection of the optical axis of the lens with the laser plane, whose axis z is normal to the laser plane, and whose axes x and y are the projection of the directions of the lines and columns of the CCD matrix in the plane orthogonal to the axis z. The coordinates of a point in this reference system are noted (Xla, Yla, Zla).

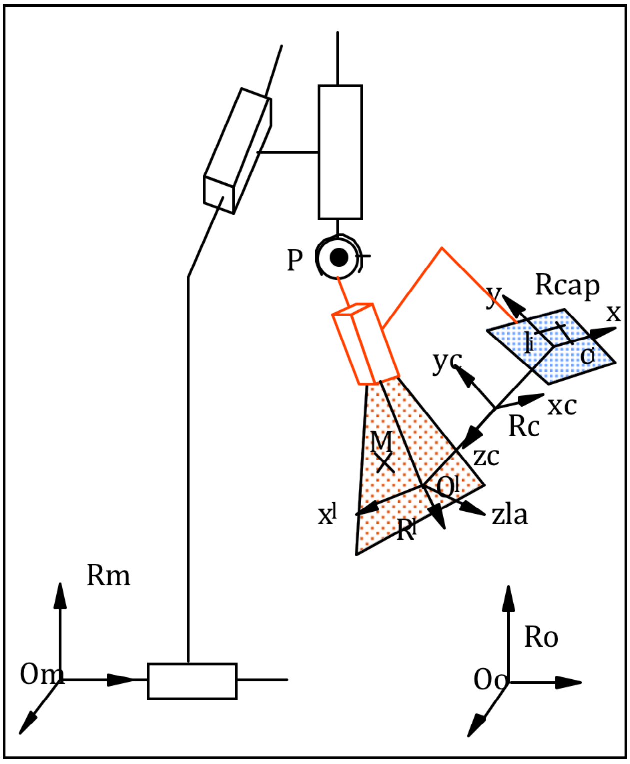

fig 2. Definition of the reference points.

Modeling in connection with the manipulating arm The manipulating arm is composed of 5 solids cinematically connected by 3 prismatic connections with Ox,Oy, Oz axes and by a discreet finger toggle-joint connection. The relative movements of the prismatic connections are identified by the position sensors X,Y, Z and allow to characterize the Omp vector. The expression of the Oom vector, with M as a point of the laser plane, can thus be extracted [5], [2], [4].

$$\overrightarrow{OoM} = \overrightarrow{OoOm} + \overrightarrow{OmP} + \overrightarrow{POla} + \overrightarrow{OlaM}$$

$$\begin{bmatrix} Xo \\ Yo \\ Zo \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & Tom_x + X + Tpla_x \\ 0 & 1 & 0 & Tom_y + Y + Tpla_y \\ 0 & 0 & 1 & Tom_z + Z + Tpla_z \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} r1 & r2 & r3 & 0 \\ r4 & r5 & r6 & 0 \\ r7 & r8 & r9 & O \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} Xla \\ Yla \\ Zla \\ 1 \end{bmatrix}$$

Modeling in connection with the CCD Camera The transformation of the camera between the object space and the image plane can be modelled according to the optical geometry laws. It is then a central projection. This model allows to establish the analytic relationship between the coordinates of a point in the object space and those of the point corresponding to the image space thanks to the chosen parameters.

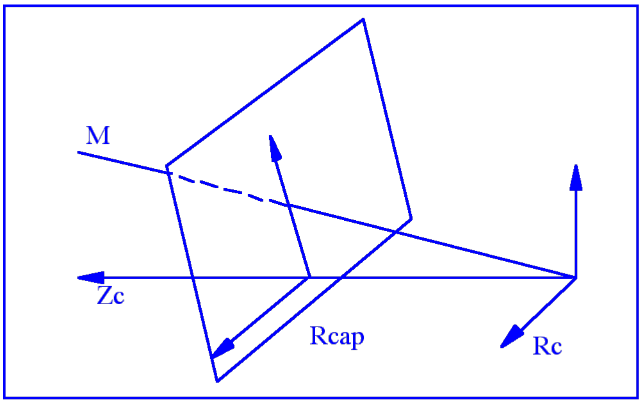

fig. 3 : Pinhole model

The pinhole model will be applied to the perspective relationship of a lens by the central projection.

So as to simplify notation, the image plane will be conventionally positioned on the same side as the object space.

The model is then made of a projection center that corresponds to the optical center of the lens, of an image plane, corresponding to the CCD matrix plane. The sensor plane is tilted in relation to the optical axis of the lens. It is characterized in the reference Rc by the following equation :

$$z = A.x + B.y + C$$

$$[Oc\,M] = \begin{bmatrix} Xc \\ Yc \\ Zc \\ 1 \end{bmatrix} \qquad [V] = \begin{bmatrix} c' \\ l' \\ \alpha \\ N \end{bmatrix}$$

$$[V] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & O \\ \frac{-A}{C} & \frac{-B}{C} & \frac{1}{C} & 1 \end{bmatrix} . [OcM]$$

$$\begin{cases} c = \frac{c'}{N} \\ l = \frac{l'}{N} \end{cases}$$

In this model, all light beams that cross the optical center cut the image plane without changing direction.

The third component of V, which is in the direction of the camera's optical axis, has no significant meaning and can be ignored. This means that each image point does not correspond to a single object point but to a single light beam [2].

This model can be generalized under the following application :

$$(l,c) = F(Xc, Yc, Zc)$$

Modeling in relation with the laser plane The system that makes up the laser beam is composed of a pinhole light diode, a lens and a set of mirrors.

The light diode is fixed on the optical axis.

From a light source, the double lens will form a plane beam that focusses at a given distance.

The lens has geometric position defects. The image is not perfectly homologous to the model computed according to the optical geometry laws.The position uncertainty of the light source on the optical axis cannot be neglected, which generates a laser beam that does not fit the plane model [3].

This laser beam can be modelled by varied geometric entities :

- a plane
- a part of a cone
- a ruled surface [2], [4].

$$0 = G(Xla, Yla, Zla)$$

Modeling the acquisition system As the third component of V acts as a free parameter, the values chosen for it will yield various object points along the beam. This means that an image point does not correspond to a single point but to a single beam in the object space. But this object point belongs to the laser plane, which conditions this free parameter[5], [2].

Therefore, in the case of a plane modeling of the laser-beam, the model of the acquisition system will be:

$$\begin{cases} Xla = \dfrac{a_1 l + a_2 c + a_3}{b_1 l + b_2 c + 1} \\ Yla = \dfrac{c_1 l + c_2 c + c_3}{b_1 l + b_2 c + 1} \\ Zla = 0 \end{cases}$$

as

$$\begin{bmatrix} Xo \\ Yo \\ Zo \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & Tom_x + X + Tpla_x \\ 0 & 1 & 0 & Tom_y + Y + Tpla_y \\ 0 & 0 & 1 & Tom_z + Z + Tpla_z \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} r1 & r2 & r3 & 0 \\ r4 & r5 & r6 & 0 \\ r7 & r8 & r9 & O \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} Xla \\ Yla \\ Zla \\ 1 \end{bmatrix}$$

hence

$$\begin{cases} Xo = X + \dfrac{a'_1 l + a'_2 c + a'_3}{b_1 l + b_2 c + 1} \\ Yo = Y + \dfrac{c'_1 l + c'_2 c + c'_3}{b_1 l + b_2 c + 1} \\ Zo = Z + \dfrac{d'_1 l + d'_2 c + d'_3}{b_1 l + b_2 c + 1} \end{cases}$$

Thus, in the case of a non-plane modeling of the laser-beam, the model for the acquisition system will be:

$$\begin{cases} Xo = X + \dfrac{a_1 l + a_2 c + a_3 + a_4 l^2 + a_5 c^2 + a_6 lc + \ldots}{(b_1 l + b_2 c + 1)^n} \\ Yo = Y + \dfrac{c_1 l + c_2 c + c_3 + c_4 l^2 + c_5 c^2 + c_6 lc + \ldots}{(b_1 l + b_2 c + 1)^n} \\ Zo = Z + \dfrac{d_1 l + d_2 c + d_3 + d_4 l^2 + d_5 c^2 + d_6 lc + \ldots}{(b_1 l + b_2 c + 1)^n} \end{cases}$$

CALIBRATION METHOD

The definition of the calibration protocole entails the study of the geometry of the reference element, which has to be simple and reachable whatever the orientation of the sensor. A calibration system is most often founded upon the measuring of a reference sphere or cube.

Calibration protocole The models of the system hold 11 to 36 parameters to be identified by measuring a reference element with perfectly known geometric characteristics. Therefore, at least 11 separate equations have to be established by measuring the reference element; they will be obtained by extraction of geometric entities of the image outlines of the CCD matrix.

The manipulating arm ensures both the sensor's X, Y, Z movements and its orientation. The sensor's movements also entail dispersions, but they are in the range of 5μm in a 1m^3 volume, which makes them neglectable by comparison with the optical sensor's accuracy. On the other hand, the calibration process has to take into consideration the low accuracy of the swivelling head. The identification of the model parameters will hence have to be carried out for each position of the head [2], [4].

Geometry of the reference element The reference element's shape is conditioned by the following constraints :

- the model
- the diffusion of the laser-beam on the surface of the object digitalized
- the visual access of the camera according to the position of the swivelling head.

Several simple geometric entities can be used, such as spheres or planes:

A *sphere* is a very interesting geometric entity, as it increases the reachability of the sensor on the reference element.

However, in the case of a non-plane modeling of the laser-beam, the nature of the impact line between the beam and the sphere is not a portion of a circle , which generates problems when processing the acquisition upon identification of the model's parameters.

Furthermore, a diffusion phenomenon of the laser beam can be noticed when the incidence angle between it and the part's surface is high. The laser beam diffuses irregularly on the edges of a spheric cap, which reduces the outline that can be used in the acquisition.

A *cylinder* has the same drawbacks as the sphere, but also reduces the reachability of the sensor.

A *plane* is also an interesting geometric entity as a reference element, as it obeys a linear equation: [2].

$$\alpha_k \cdot X_i + \beta_k \cdot Y_i + \chi_k \cdot Z_i + \delta_k = 0$$

The point Mi belongs to the plane k which is defined by the parameters α, β, χ and δ in the reference Ro.

As the modeling of acquisition systems shows transfer functions which are rational fractions whose denominators are identical, the linearization of the equation showing that the point M belongs to the reference plane , as a function of the parameters of the transfer functions, is made possible:

$$\alpha_k \cdot Xo + \beta_k \cdot Yo + \chi_k \cdot Zo + \delta_k = 0$$

as

$$\begin{cases} Xo = X + \dfrac{a'_1 l + a'_2 c + a'_3}{b_1 l + b_2 c + 1} \\ Yo = Y + \dfrac{c'_1 l + c'_2 c + c'_3}{b_1 l + b_2 c + 1} \\ Zo = Z + \dfrac{d'_1 l + d'_2 c + d'_3}{b_1 l + b_2 c + 1} \end{cases}$$

hence

$$\alpha_k \cdot \left(X + \frac{a'_1 l + a'_2 c + a'_3}{b_1 l + b_2 c + 1}\right) + \beta_k \cdot \left(Y + \frac{c'_1 l + c'_2 c + c'_3}{b_1 l + b_2 c + 1}\right) + \chi_k \cdot \left(Z + \frac{d'_1 l + d'_2 c + d'_3}{b_1 l + b_2 c + 1}\right) + \delta_k = 0$$

hence

$$l K_k\ b_1 + c K_k\ b_2 + l\,\alpha_k \cdot a'_1 + c\,\alpha_k \cdot a'_2 + \alpha_k \cdot a'_3 + l\,\beta_k\, c'_1 + c\,\beta_k\, c'_2 + \beta_k\, c'_3 + l\,\chi_k\, d'_1 + c\,\chi_k\, d'_2 + \chi_k\, d'_3 = -K_k$$

$$K_k = \alpha_k X + \beta_k Y + \chi_k Z + \delta_k$$

So as to allow for the visual access of the camera, according to the numerous positions of the head, and to reduce the incidence angle between the laser beam and the reference surface, the reference element is a facetted sphere.

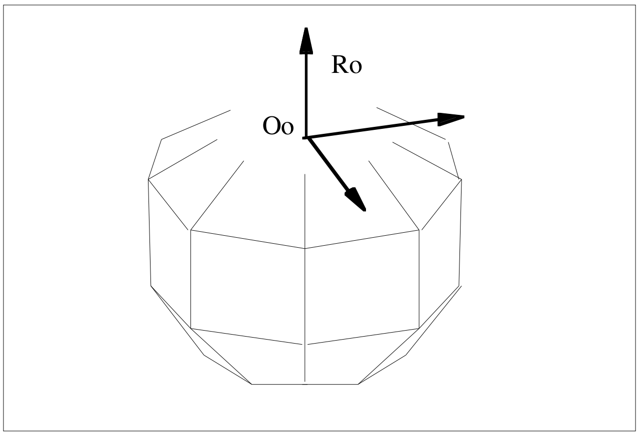

fig.4. Geometry of the reference element

It is a set of 24 planes; parallel two by two and positioned symetrically in relation to a common center Oo. It was realized after adjustments and then measured on a high precision measuring machine, which allows to get the equations of the 23 facets the sensor can reach, along a Ro' reference point related to 3 facets.

Calibration method [2], [4] It is conducted in 4 stages :

- digitalization of the reference element in 2 sweepings, 3 sections and 3 heights in the camera scope, i.e 18 acquisitions.

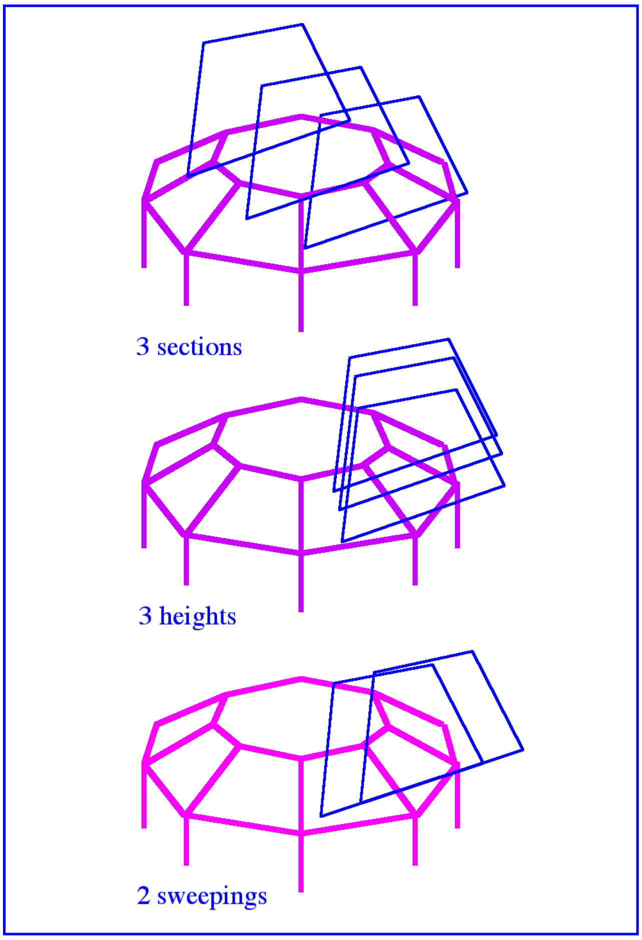

fig. 5 Acquisitions

- extraction of the points for each acquisition i.

In the camera plane, the intersection of the laser beam with the facetted sphere's surface is a set of points presented in 1 to 3 curve segments .The nature of the model of these curves is in function of the laser beam model, whose generic geometric entity extracted is a set of points belonging to a plane k. The points that will allow to build up an acquisition system in order to identify the parameters of the model, will be chosen so as to get a complete sampling of the camera scope. This is carried out by the operator as it depends on the position of the swivelling head.

- building up the equations.

A point (Xoj, Yoj,Zoj) belonging to the plane k will correspond to each point j (lj,cj)

$$lj\, K_k\, b_1 + cj\, K_k\, b_2 + lj\, \alpha_k \,.\, a'_1 + cj\, \alpha_k \,.\, a'_2 + \alpha_k \,.\, a'_3 + lj\, \beta_k\, c'_1 + cj\, \beta_k\, c'_2 + \beta_k\, c'_3 + lj\, \chi_k\, d'_1 + cj\, \chi_k\, d'_2 + \chi_k\, d'_3 = - K_{ki}$$

$$K_{ki} = \alpha_k\, Xi + \beta_k\, Yi + \chi_k\, Zi + \delta_k$$

An equation can be deduced from each point extracted, where b_1, b_2, a'_1, a'_2, a'_3, c'_1, ... are the unknowns.

- Solving the equation system.

It means solving a linear constrained system of 72 equations with 11 to 36 unknowns.

CONCLUSION

The process allows to take into consideration both the inner geometric variations of the sensor and its situation in the Tridimensional Measuring Machine's space. The use of a facetted sphere as the reference element increases the reachability of the sensor while reducing the incidence angles of the laser beam on the digitalized surface. We can thus increase the number of possible positions for the swivelling head, by which we will then be able to calibrate the sensor and make it possible to digitalize heretofore hidden surfaces.

The results obtained show that the accuracy varies with the coordinates l and c of the CCD matrix, and even more so on its edges. The error on the slope of the straight lines of the least square which allow to calculate the intersection point between the laser beam and two contiguous facets, is in the rage of 0.5% in the middle and 4% at the edges of the CCD matrix. The increased number of errors on the edges is due to lens defects that increase the blurring of the impact line. This increase reduces the intensity peaks, which renders the subpixel processing more difficult and increases the number of errors. Consequently, to improve the sensor's accuracy, the calibration has to be carried out with points obtained in the central part of the object plane.

The experimental results have allowed to validate the proposed method, but the assessment of the accuracy reached remains a problem to solve. This accuracy varies according to the zone used on the CCD matrix; it would then be theoretically impossible to define a mapping of the accuracy reached according to the coordinates given by the CCD matrix and to the angle between the laser plane and the digitalized surface.

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