Ambulatory Measurements Of Dimensional Quantities By Laser Triangulation Under Structured Lighting

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Abstract - The first part of the paper, mainly of tutorial nature, will be devoted to the presentation of the basic principles of 3D measurements by triangulation under lighting structured by laser planes. The metrological aspects will then be considered, namely the calibration of the measuring set-up. Finally, a series of industrial applications developed in the laboratory and oriented towards the conception of new field instruments (non-contact measurement of linear objects, of the angle between planes, of the diameter of cylinders, …) will be presented. The experimental results show a general accuracy of the order of one percent.

I. Principles

Laser triangulation is an optical technique of analysis aiming to the acquisition of dimensional information about various objects by purely geometrical interpretation of an image obtained on an appropriate detector and resulting of the interaction of a laser beam with the object. This non-contact method is of course an essential asset allowing remote measurements (let us think to places of difficult access or in hostile environment), without wear nor influence on the object under test.

The basic principle of laser triangulation is well known and will simply be recalled. The most usual case is this of a narrow beam of a laser diode impinging on a target, creating a spot observed by a PSD (position-sensing detector). The impact dot on the PSD (which is a 1-D sensor) is in triangular relation with the distance D of the target with respect to the optical center of the detection system (fig.1). Let us mention that for that the spot is viewed by the sensor in each situation of distance and attitude of the target, it must been in the view field of the detection system but also the target surface must be (at least partially) diffusing, what is the case of the large majority of objects (to the notorious exclusion of mirror surfaces).

Fig. 1 - Laser triangulation

In order to enrich the information relevant to the object under test (the target), the spot must be displaced for instance by way of a scanning system or by displacing the object by appropriate movements. An alternative is to illuminate the target by a more complex structure than the simple dot pointer. This kind of "active vision" is called "structured lighting". The most known structure is this of a laser layer (or plane). The detection system must simultaneously also be enriched : the 1-D PSD sensor is replaced by a 2-D sensor as are equipped every black-and-white cameras (CCD matrices, more recently, CMOS matrices).

A. Structured lighting : use of a laser plane

Passing the laser beam through a "line generator" (this optical component is easily available on the market, but the Canadian firm LASIRIS is the only one to propose items giving lines with uniform intensity) produces a plane whose intersection with the target is a line observed by a conventional black-and-white camera (fig.2).
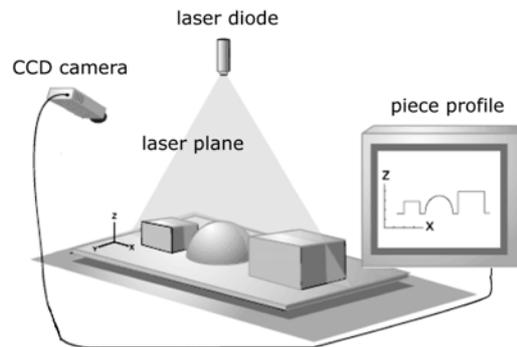

Fig.2 - Target illuminated by a laser plane structured lighting

The important feature of this arrangement is that each point of the laser line transposed in the image plane (the camera CCD plane) corresponds to one point of the real space observed by the camera, with the restriction that this point belongs to the laser plane. If the position of this latter is perfectly defined with respect to the camera, this structuration of the 3-D space has the consequence to reduce this space by one degree of freedom ; this allows a one-to-one correspondence between any pixel of the laser line in the image plane and the corresponding point in the object plane (i.e. the laser plane generating the curve of concern) (Fig.3)
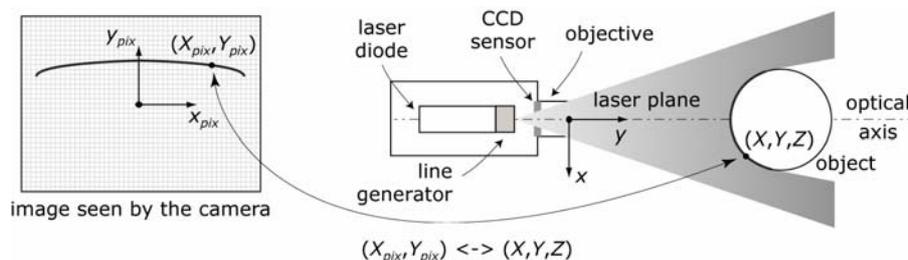
Fig.3 - One-to-one correspondence between the image plane and the object plane

By sweeping (e.g. by a scanning process) the entire object, it is thus possible to reconstitute the complete morphology of this 3D object, at least for what the camera sees.

Our thematic research is focussed on the dimensional characterization of objects of diverse shapes with the objective to achieve a metrological performance at the industrial level. Furthermore, ambulatory and field applications are aimed using low cost components.

Before detailing specific applications, other general aspects are to be considered, as the extraction of the pertinent laser lines and the calibration of the measuring system.

B. Extraction of the laser lines

An image processing algorithm allows the extraction of the laser lines intercepted by the object under test by isolating them from the rest of the scene. This algorithm is specifically dedicated to the expected type of line to be kept and thus depends on the application.

An interference filter of narrow band-with centered on the laser diode wavelength and placed in front of the entrance camera pupil, realizes a substantial part of the task by significantly rejecting the ambient light. Some additional image processing steps are still necessary to suppress the noise surrounding the curves.

Concretely, two pictures, with the laser diode respectively on and off, are taken in sequence and then subtracted. It remains only the laser curves of interest plus a multitude of parasitic pixels, due for instance to the variation of the scene lighting or of the camera position between the two shots, quantification errors during the image digitalization etc.

A dichotomic cleaning of the image follows by selection or rejection of each pixel according to a threshold depending on the application and judiciously chosen by way of the image histogram. We then identify the

different "bodies" (sets of interconnected white pixels) remaining in the image. The bodies which are too small or these the shape of which is to far from this of the laser lines corresponding to our application (often, curves with too high curvature) are rejected. A specific algorithm (e.g. computation, for each column, of the pixel ordinates weighted by their intensity) allows us to achieve a sub-pixel resolution for the remaining lines. Finally, a curve smoothing alleviates the harshness of the lines due e.g.. to discretization effects.

C. Calibration of the measuring system

The goal of this step is two-folds:
- to determine the geometrical parameters of the measuring set-up
- to correct the optical aberrations of the camera

The geometrical parameters of the measuring set-up to be accurately known are typically the focal length of the camera objective and the attitude of the laser plane with regard to the camera plane (distance and tilt angle). The calibration procedure lays on a certain amount of measurements made at different distances on objects of known characteristics. An optimization algorithm using the "steepest descent method" extracts from these measurements the most probable values for those parameters.

The optical aberrations of the camera are mainly identified and quantified by observing the image of a checker pattern.

II. First application: measuring the diameter of cylindrical objects (ref. 1, 2)

The industrial situations where it is important to know, at distance, the diameter of cylindrical pieces (tubes and stems of all kind) are numerous. A specific application which deserved a particular interest of our laboratory was the ambulatory measurement of diameter of trees in forest (ref.1).

A. Set-up geometry

In a first step, we consider a perfectly cylindrical object of vertical axis, the camera being supposed in the horizontal plane. Fig.4 gives a 3-D view of the set-up. The laser plane illuminating the cylinder is slightly tilted with regard to the horizontal, with its normal in the vertical plane.
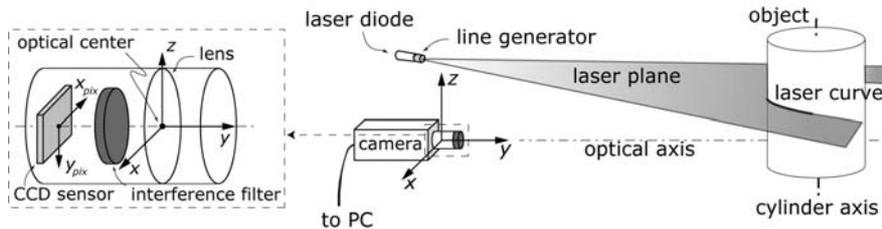
Fig. 4 - Set-up configuration. 3-D view

B. Radius calculation

The analysis of the laser line in the image plane allows us to access to the cylinder radius R. We observe that the projection of the laser curve in the x-y plan of the camera is a arc of circle the radius of which is the searched quantity. For the computation of this radius, we use the property that a circle is entirely defined by 3 of its tangents. We choose the straight lines $P_{2'}P_{3'}$, $OP_{2'}$ et $OP_{3'}$ respectively tangent to the circle at the points P_1, P_2 et P_3 (cf. Fig. 5 where we supposed the realistic situation of a de-centered aim).
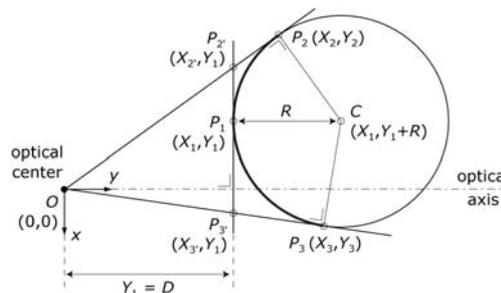

Fig.5 - «Three-tangents method». Top view in the object plane. De-centered aim

Their knowledge only needs the determination of the distance D $(= Y_1)$, i.e. the ordinate of the point P_1 (proximal point in the direction of the optical axis), and the abscissas $X_{2'}$ et $X_{3'}$ of the two intersection points of

the tangent $P_2 \cdot P_3$, with the two others. The points P_2, et P_3, are non material but their coordinates in the object plane can be deduced form the abscissa of P_2 et P_3 and the ordinate of P_1 in the image plane. The searched radius is directly deduced of quantities Y_1, X'_2 et X'_3.

$$R = \frac{Y_1 \left(X_{3'} - X_{2'} \right)}{\sqrt{X_{2'}^2 + Y_1^2} + \sqrt{X_{3'}^2 + Y_1^2} - \left(X_{3'} - X_{2'} \right)} \tag{1}$$

The radius is thus determined from partial coordinates of points perfectly identifiable in the image plane and transposed in the object plane through the one-to-one correspondence mentioned above.

C. Justification of the « Three-tangent method »

The pertinence of our method, with regard to others more immediate in appearance, is justified by the analysis of the laser curve in the image plane. We showed that our method perfectly circumvents the restrictions induced by the general shape of the curve observed on the CCD sensor, because it lays only on partial coordinates accurately known. More classical methods, as the reconstruction of a circle by both coordinates of three of its points, should be less robust.

D. Generalization to a randomly tilted cylinder

The generalization of a cylinder of random orientation is essential. Let us for instance think to the diameter determination of pipes in technical sheaths of difficult access.

The projection of the laser curve onto the camera plane is this time no more an arc of circle but an arc of ellipse (Fig. 6). The three tangent method remains of application : if we know the orientation of the cylinder axis (two angles define it, α-β or θ-φ, see Fig. 7), it is possible, by successive rotations of reference axes, to come back to the preceding situation of vertical cylinder and thus to compute the radius through formula (1). To know this orientation, two laser planes are here necessary (once again, the firm LASIRIS, is the only one to offer multiline generators) : they produce two laser curves on the target, the representation of which in the image plane is given on Fig. 8. We showed in ref 2 that the mutually relative arrangement of these two curves allows the two angles characterizing the cylinder axis orientation to be known.
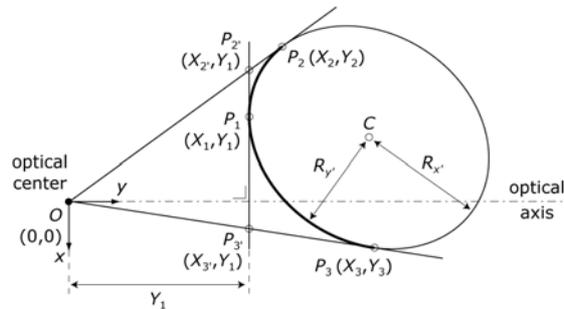

Fig. 6 - Tilted cylinder projection. Top view in the object plane
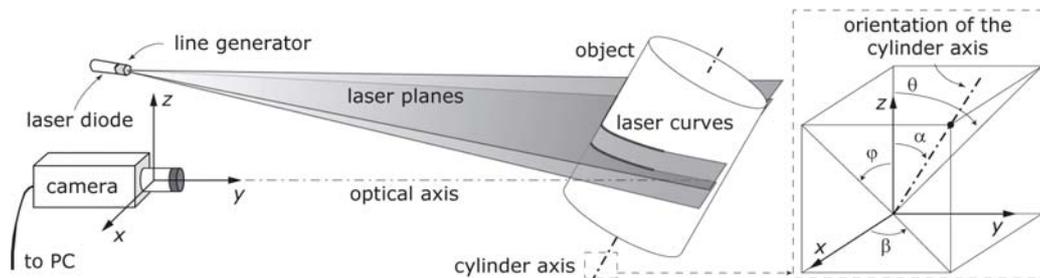

Fig.7 - Set-up for the determination of randomly tilted cylindrical objects (3-D view)
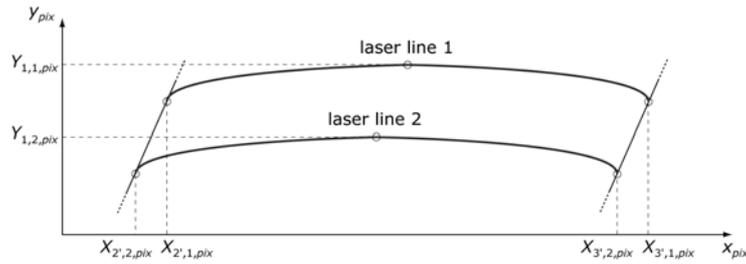
Fig. 8 - Computation of the cylinder orientation. View in the image plane

E. Results

A prototype was built (10 mW - 670 nm laser; PC-connected monochrome camera) and a measuring campaign performed. The results show that for 90% of the tests made on cylindrical pieces of various diameters (10 to 30 cm) and tilts, at various distances (50 cm - 2 m), the relative error on the diameter is below 1%.

III. Second application : dimensional measurements in the building sector (ref.3)

The goal is here to develop an instrument able to measure in a comfortable way the main dimensional quantities of concern in the building sector in general (construction, renovation, technical audit…). The functionalities kept in mind are to measure: (i) the angle between 2 plane surfaces ; (ii) the absolute orientation of a plane wall ; (iii) the distance between two parallel planes ; (iv) the length of any straight segment. Once again, the aim of our instrument must be random.

A. Principal components analysis (PCA)

PCA is used for determining the best plane from a collection of points belonging to this plane. The higher is the amount of laser planes, the more accurate is the result. We actually used 3 laser planes.

B. Application to our instrument

It is now easy to imagine how to implement our 4 functionalities :

(i)   To measure the angle between two planes, we aim to these planes and simply extract from the PCA the parameters of their normal vectors (expressing the direction of these planes). The computation of their scalar product directly give the searched angle (Fig. 9)

(ii) If we also have a reference of horizontality for our instrument (e.g. by way of a bubble level), the absolute orientation of a wall is determined (cf. Fig 10).

(iii) To measure the distance between two walls supposed parallel, we proceed in two steps, for taking into account the restriction that we don't necessary have access to these walls. We successively aim to each of them, by taking care that from one aim to the second, our instrument is rotated around a fixed point. The distance between the two walls is easily deduced from the equation of their plane by summing the distance of each of them to the fixed rotating point (Fig.11).

(iv) The PCA will not be applied for the computation of the length L of a segment (cf. Fig.12), which will be simply deduced from the 3-D coordinates of their extremities (X_l,Y_l,Z_l) et (X_r,Y_r,Z_r), observable on the laser line carefully aligned on the segment to be measured.

$$L = \sqrt{\left(X_l - X_r\right)^2 + \left(Y_l - Y_r\right)^2 + \left(Z_l - Z_r\right)^2} \qquad (2)$$

These extremities are not always accurately identifiable by simple image observation, what requires in this case the application of algorithms specific to the situation.
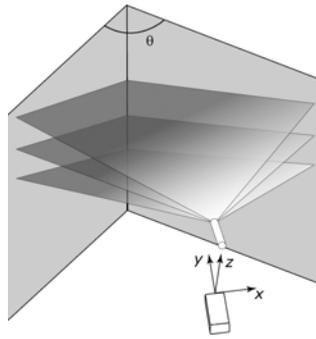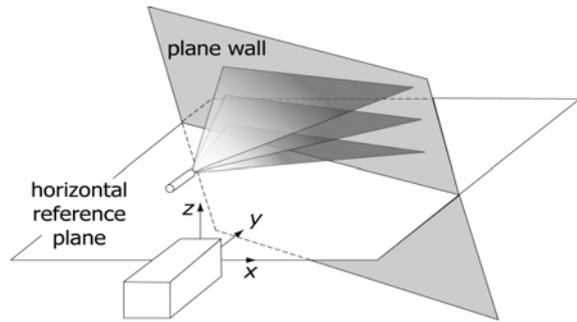
Fig. 9 - Measurement of angle between two planes

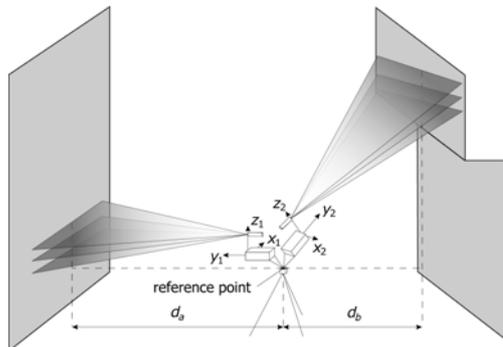Fig.10 - Absolute orientation of a plane
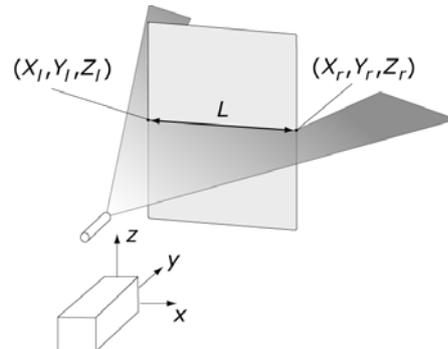

Fig.11 - Distance between two parallel walls

Fig.12 - Length of a segment

C. Results

Once again, a measuring campaign was organized, varying the observing distances and aims, for different angles between the planes and different lengths of segments. The following global uncertainties were obtained : 2 degrees on the angle between two planes ; 1% on the distance between parallel walls and on the length of a straight segment.

IV. Conclusions

The object of this paper was to show, through two contrasted types of applications, the potential of the method of laser triangulation under structured lighting in ambulatory condition. The way is open to multiple innovative industrial realizations.

References

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