Automatic Feature Recognition in Coordinate Metrology

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KEYWORDS : Coordinate metrology, Feature recognition, Gauss Map

In coordinate measurement, the user generally should select the feature type before operating the coordinate measuring machine (CMM) to collect data points from the surface of the target feature. In this paper, an automatic feature recognition algorithm is presented to free the CMM user from specifying the feature type. The probing direction of the measured data points are used to estimate the potential feature type, and the existing fitting algorithms for the features are used to compute the parameters and tolerances of the features. The tolerances are then used to evaluate the validity of the estimation of the feature type. Using such an algorithm, the user can measure the target feature without specifying the type, and the type of the feature is automatically recognized by the CMM software.

Manuscript received: January XX, 2011 / Accepted: January XX, 2011

NOMENCLATURE

Probing vector = probing vector is the vector which is used for directing the probe tip towards the part surface

α = the threshold for the angle between the probing vector and the normal of the point to be measured

$\{p_i\}_{i=1}^{n}$ = a dynamic set of measured points

n_i = the normal of the measured surface at p_i

v_i = the probing vector for p_i

δ_i = the angle between n_i and $-v_i$

1. Introduction

According to the ISO 10360-1 (2000) standard, a “coordinate measuring machine (CMM)” is a “measuring machine with the means to move a probing system and capability to determine spatial coordinates on a measurand surface”. Its ability to sample points in a 3D space in combination with the CMM software allow it to evaluate any geometric or dimensional tolerance of the measurand as long as the probe can approach the feature element.

An operator may control a Computer Numerical Controlled (CNC) CMM in two modes [1], one is computer-controlled operation with an inspection program, usually in DMIS (Dimensional Measuring Interface Standard) format, and the other is to manually operate the joystick of the CMM to control the motion, to implement the point-based measurement with a touch trigger probe. In the latter mode, the operator need to select the feature type before measuring a feature element, and this is tedious for the operator, especially when the part is big in size and there are many geometric elements needed to be inspected. So an algorithm that can automatically recognise the feature type during the point probing process will free the operator from selecting the feature type time by time and facilitate the inspection operation.

Feature recognition has been used in several areas. One that is similar to meaning of this paper is that used in reverse engineering [2], [3]. In reverse engineering, a triangular mesh is reconstructed from the point cloud that acquired from the surface of a physical model, generally using a scanner. The portions of mesh which represent different features are recognised, generally with the help of the normal and curvature of the vertex, and the mesh is decomposed for subsequent process. However, for the problem considered in this paper, the data points are generally much sparser than that in reverse engineering and there is no mesh.

In this paper, an automatic recognition algorithm for the fundamental features in coordinate metrology is presented, mainly based on the Gauss map. The fundamental geometric features in coordinate metrology are shown in Section 2, and the Gauss maps of the geometric features are given in Section 3. A pseudo-Gauss map of the geometric feature to be recognized is given in Section 4. The feature recognition algorithm is presented in Section 5, and conclusions in Section 6.

2. Geometric Features in Coordinate Metrology

The fundamental geometric features in coordinate metrology are shown in Fig 1, including spheres (see Fig. 1(a)), cylinders (see Fig. 1(b)), cones (see Fig. 1(c)), planes (see Fig. 1(d)), a line on a plane (see Fig. 1(e)) and a circle on a cylinder (see Fig. 1(f)).

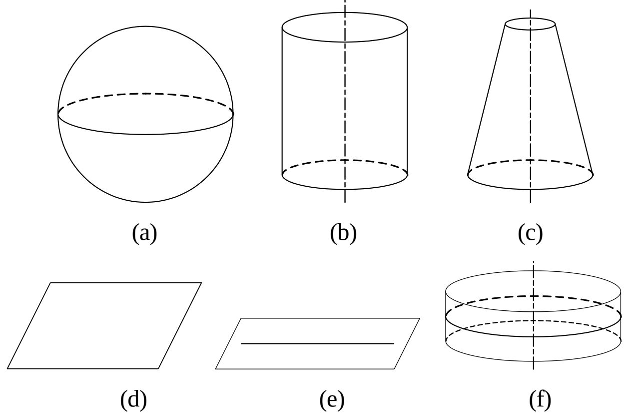


Fig. 1 Geometric feature elements in coordinate measurement: (a) a sphere; (b) a cylinder; (c) a cone; (d) a plane; (e) a line on a plane; (f) a circle on a cylinder.

In coordinate measurement, the line or circle located at the corner of a measurand can be measured directly. When a line is measured, it is generally a line on a plane, especially a long thin plane, and when a circle is measured, it is generally a circle on a cylinder, especially a very short cylinder.

Using a touch trigger probe, the angle between the inverse of the probing direction and the normal should be less than a threshold α (see Fig. 2(a)) to minimise the skidding between the probe tip and the measurand. The skidding between the probe tip and the measurand may introduce significant uncertainty into measured result, and cause the wear of the probe tip.

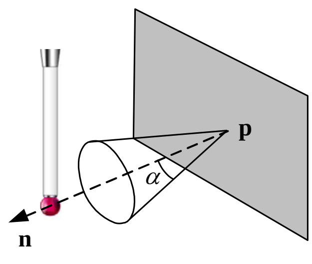


Fig. 2 Probing direction using a touch trigger probe.

Different minimum number of measured points is needed need to compute the substitute geometry of different feature elements. With at least two, three, four, five, six points, a line, a circle or a plane, a sphere, a cylinder, a cone can be computed, respectively. To evaluate the tolerance of the element and get a reliable result, much more points should be probed in practice [4]. The least-squares fitting algorithms for the substitute geometric elements are described in [5], and details are out of the scopes of this paper.

3. Gauss Maps of Geometric Features

In differential geometry, the Gauss map, named after Carl F. Gauss, maps a surface in Euclidean space R^3 to a unit sphere S^2. Given a surface X lying in R^3, the Gauss map is a continuous map G: $X \to S^2$ such that $G(p)$ is the normal vector to X at p [6].

The Gauss map can be defined if and only if the surface is orientable, and it can always be defined locally, i.e. on a small piece of the surface. All the geometric feature elements shown in Fig. 1(a)-(b) are orientable surfaces. So a Gauss map can be constructed for each of them.

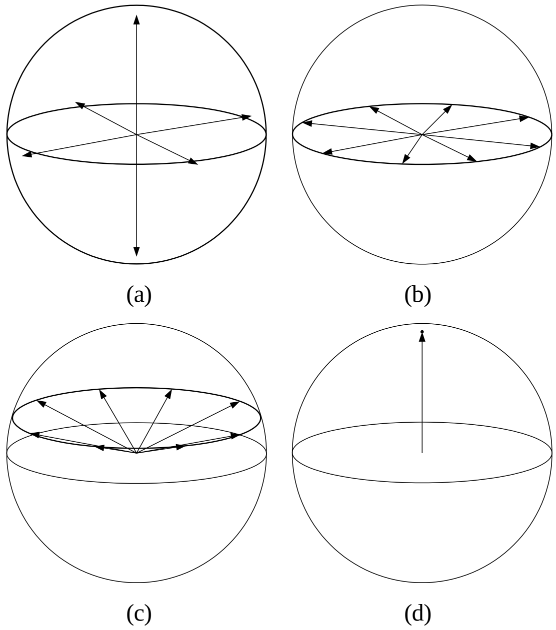


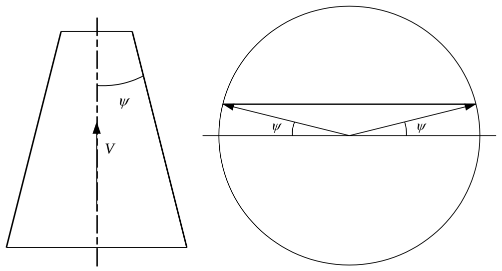
Fig. 3 Gauss map of (a) a sphere, (b) a cylinder, (c) a cone, (d) a plane.

The Gauss maps of the sphere, the cylinder, the cone and the plane are of apparent characteristics. It is not difficult to work out that the Gauss map of a plane is a point on the unit sphere (see Fig. 3(d)), and the point is the intersection of the unit sphere and a ray that is originated from the center of the unit sphere and parallel to the normal of the plane. The Gauss map of a portion of a plane is still a point.

The Gauss map of any sphere is a unit sphere (see Fig. 3(a)), and the Gauss map of a portion of a sphere is a portion of the unit sphere. A portion of the sphere can be transformed into a portion of a unit sphere using a uniform scaling, and the resulted is the Gauss map of the portion of the sphere.

The Gauss map of a cylinder is a great circle on a unit sphere (see Fig. 3(b)), and it is the intersection between the unit sphere and a plane passing through the center of the unit sphere and oriented along the axis of the cylinder. The Gauss map of a portion of a cylinder is a portion of the great circle, i.e. an arc. If the cylinder is projected on a plane perpendicular to the axis of the cylinder, and transformed into an arc with unit radius, and then translated the center of the arc to the center of the unit sphere, the resulted arc is the Gauss map of the portion of the cylinder.

The Gauss map of a cone is also a circle on a unit sphere (see Fig. 3(c)). However, it is not a great circle. Let c be the center of the unit sphere, ψ be the apex semi-angle of the cone and V is the vector of the cone axis that points to the apex of the cone. The Gauss map of the cone is the intersection between the unit sphere and a plane passing through $c+\sin(\psi)V$ and oriented along V (see Fig. 4).



(a) (b)

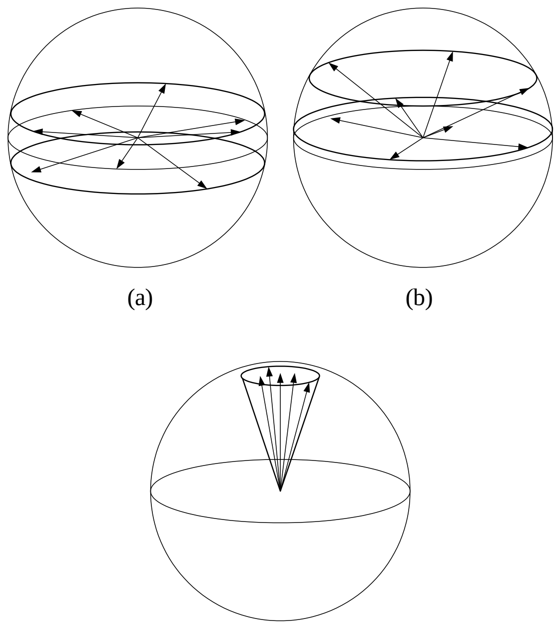
Fig. 4 Front view of a cone (a) and its Gauss map (b).

In coordinate measurement, a measured line is on a certain plane (see Fig. 1(e)), and a measured circle is on a certain cylinder (see Fig. 1(f)). If a line and a circle are considered as a degenerated piece of the plane and the cylinder, respectively, Gauss maps can also be constructed for these two feature elements. The Gauss map of a line is same to that of the plane, and the Gauss map of a circle is same to that of the cylinder. As a result, the Gauss map can not be used to differentiate a line and a plane, or a circle and a cylinder in feature recognition in coordinate metrology.

4. Pseudo-Gauss Maps of Geometric Features

The Gauss maps of the plane, cylinder, sphere, and cone are different, and in coordinate measurement the operator is suggested to probe a point along a direction as close to the normal of the point as possible. So in theory a Gauss-like map, which is the result of mapping the probing vectors of a feature element onto a unit sphere and is called pseudo-Gauss map in this paper, can be used recognise the feature type.

However, it is nonsensical to require the operator to probe a point exactly along the normal of the point. That means the pseudo-Gauss map is different from the Gauss map of the feature element of each type. The characteristic of the pseudo-Gauss map for the geometric feature element of each type is discussed one by one in the following.



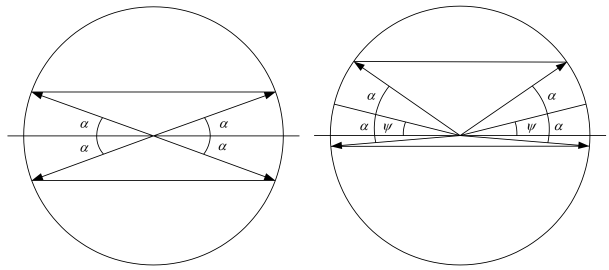
(a) (b)

(c)

Fig. 5 The pseudo-Gauss maps of (a) a plane, (b) a cylinder, and (c) a cone.

All vectors of the pseudo-Gauss map of a plane are generally not identical to each other and are located inside a small cone zone (see Fig 4(a)). Let $\delta = \sum \delta_i \big/ n$, and $\beta = \max(\{|\delta_i - \delta|\}_{i=1}^{n})$. A cone with apex semi-angle β and apex at the center of the unit sphere can contain all the vectors.

All vectors of the pseudo-Gauss maps of a cylinder and a cone generally do not point to a same circle any more, and they point to a band on the sphere (see Fig 4(b) and (c)). Let $\phi = \max(\{\delta_i\}_{i=1}^{n})$. If $\{v_i\}_{i=1}^{n}$ is considered as a set of points, a least square plane can be fitted to $\{v_i\}_{i=1}^{n}$. For a cylinder, the error of the plane does not exceed $2\sin(\phi)$ (see Fig. 6(a)). For a cone with apex semi-angle ψ, the error of the plane does not exceed $\sin(\psi+\phi)-\sin(\psi-\phi)$ = $2\sin(\psi)\cos(\phi)$ (see Fig. 6(b)). However, as the pseudo-Gauss maps of the cylinder and the cone are too similar, and ψ is unknown, so the pseudo-Gauss map can not be used solely to differentiate them.



(a) (b)

Fig. 6 Front view of and the pseudo-Gauss maps shown in Fig. 5(a) and Fig. 5(b).

For a sphere, it is difficult to figure out a characteristic from the pseudo-Gauss map. Generally at most half of a sphere can be approached using a tough trigger probe, and the vectors of the pseudo-Gauss map span over half of the unit sphere. However, for some measurand, there may be only a partial sphere, and the area can be approached by the touch trigger probe is then quite limited. In this case, the difference between the pseudo-Gauss maps of a sphere and other features is not apparent. So other information is generally needed to recognise a sphere.

5. Feature Recognition

There is another characteristic of the probing vectors that can be used to recognise the types of the feature elements. In coordinate measurement, a line is on a plane, and a circle is on a cylinder. Thus the normal of the line is co-planar, so do for the cylinder, but not the other features. As the angle between v_i and $-n_i$ is constrained to be less than α. So when a line or a circle is measured, the probing vectors are nearly located on a plane, but not for a feature of other types.

Noted that there is a difference between the probing vector and the normal of the measured point. The probing vectors cannot be strictly co-planar. To make the co-plane test robust, the bounding box of the point set $\{p_i\}_1^n$ is computed and let the length of the bounding box be l. A least square plane can be fitted to $\{p_i\}$ and $\{p_i + l v_i\}$. If the error of the plane does not exceed $2l\sin(\alpha)$, the probing vectors are considered as co-planar; otherwise, not co-planar.

Using the pseudo-Gauss maps and co-plane test given above, the features can be recognized as followed:

(1) If two points are acquired, a line is the only possibility. If the angle between the two probing vectors does not exceed 2α, a line is computed.

(2) If three points are acquired, the feature element may be a line, a plane or a circle. If the three probing vectors are nearly co-planar, the feature element may be a line or a circle. If the pseudo-Gauss map is inside a small cone, the feature element may be a line or a plane; otherwise, if the pseudo-Gauss map is nearly co-planar, the feature element may be a circle.

(3) If four points are acquired, the feature element may be a line, a circle, a plane or a sphere. If the four probing vectors are nearly co-planar, the feature element may be a line or a circle. If the pseudo-Gauss map is inside a small cone, the feature element may be a line or a plane; otherwise, if the pseudo-Gauss map is nearly co-planar, the feature element may be a circle; otherwise, the feature element may be a sphere.

(4) If five points are acquired, the feature element may be a line, a circle, a plane, a sphere or a cylinder. If the five probing vectors are nearly co-planar, the feature element may be a line or a circle. If the pseudo-Gauss map is inside a small cone, the feature element may be a line or a plane; otherwise, if the pseudo-Gauss map is nearly co-planar, the feature element may be a circle or a cylinder; otherwise, the feature element may be a sphere.

(5) If six or more points are acquired, the feature element may be a line, a circle, a plane, a sphere, a cylinder or a cone. If all probing vectors are nearly co-planar, the feature element may be a line or a circle. If the pseudo-Gauss map is inside a small cone, the feature element may be a line or a plane; otherwise, if the pseudo-Gauss map is nearly co-planar, the feature element may be a circle, a cylinder or a cone; otherwise, the feature element may be a sphere.

Apparently, there is still ambiguity in the above test. The method to conquer the ambiguity is to compute the substitute geometries and evaluate the corresponding error, and the one with the minimum error is the correct answer. The flowchart of the algorithm is shown in Fig. 7.

In Fig. 7, ε_{line}, ε_{circle}, ε_{plane}, $\varepsilon_{cylinder}$, ε_{cone}, ε_{sphere} are the error of the computed line, circle, plane, cylinder, cone, sphere, respectively. τ is a error threshold for the feature elements set by the operator, and N is the maximum point number for a feature element.

There are several suggestions for the application of the algorithm:

(1) When a plane is measured, the first three points are suggested to be not co-line.

(2) When a cylinder or a cone is measured, the first three points are suggested to locate nearly on a cross-section, but not the fourth point.

(3) When a sphere is measured, the first three points are suggested to locate nearly on a great circle, and the fourth point is suggested to locate nearly on the polar point.

As long as the above suggestions are satisfied, the algorithm is robust for all the features. If the above suggestions are not satisfied, and the sampled points are not adequate, the algorithm may fail to recognise some feature elements and report an error. If the sample points are adequate, no matter the suggestions are satisfied or not, the algorithm is robust for any feature considered in this paper.

6. Conclusions

A feature recognition algorithm is presented in this paper to facilitate the operator when the motion of the CMM is controlled using a joystick. With such an algorithm, the operator need not specify the feature type before measuring a geometric element. The operator need only probe the points on the geometric element, and the feature type will be recognized automatically and the parameters of the substitute geometric element are then to be computed using an algorithm same as before. So a “smart” CMM will be obtained as a result.

ACKNOWLEDGEMENT

The second author is supported by the National Natural Science Foundation of China (Project No.: 61070125).

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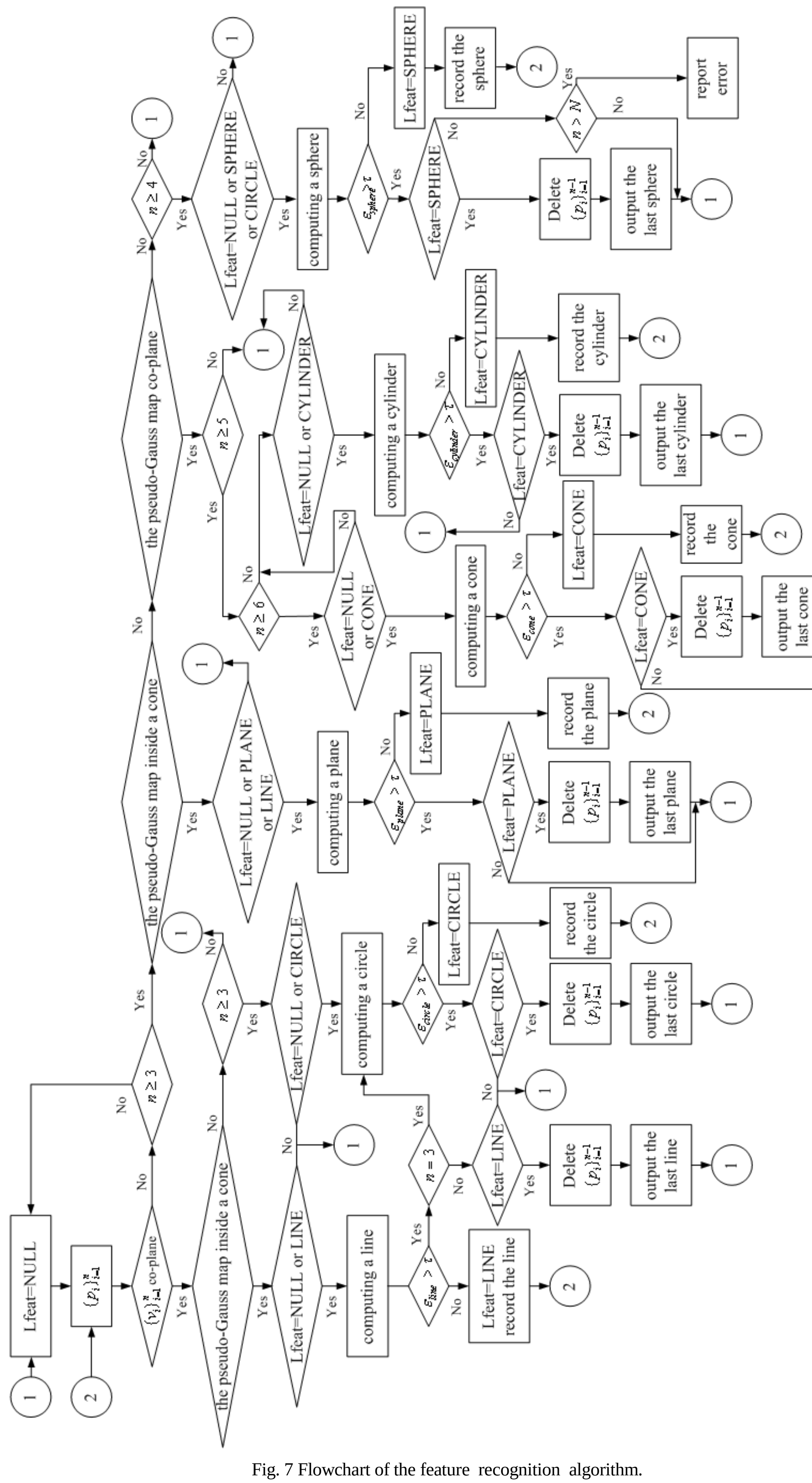

Fig. 7 Flowchart of the feature recognition algorithm.