Automated Extraction of Dimensional Inspection Features from Part CAD Models

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Abstract

Metrological inspection planning is among the least explored CAPP domains. This paper examines the basic issues involved in automated dimensional inspection planning that works within an environment of a Generic CAPP Support System. A new algorithmic approach based on multi-attributed spatial graphs is developed for extracting inspection features. The features of specific interest to the planner are selected by applying a sequential filtering method.

Key words: Dimensional Measurement, Feature recognition, Computer-aided inspection process planning

1.

1. Introduction

Success in the implementation of computer-integrated manufacturing (CIM) and /or concurrent engineering (CE) depends, *inter alia*, on the degree to which the planning of the various of manufacturing processes can be automated through computerization. The traditional response to this problem has been through the development of a set of isolated computer-aided process planning (CAPP) modules each addressing a different process (machining, forming, etc.). However, despite its importance to industry, the process of inspection has not yet received due attention in CAPP literature. This paper addresses this gap.

A computer-aided inspection process planning (CAIPP) system needs to include automated or semi-automated modules capable of identifying and recognizing the dimensional inspection features along with the associated inspection constraints. Next, it should be able to recommend an inspection method for each dimensional inspection feature. Finally, the resulting inspection operations need to be integrated into an overall inspection plan.

Although much of the inspection carried out in industry continues to be conducted using conventional metrological equipment, most previous work on CAIPP has been directed towards inspection operations performed on coordinate measuring machines

(CMM). For instance, there were seven basic types of CAIPP systems reported in literature by 1994 (Juster *et al.* 1994). Significantly, all the seven types were directed towards CMM-based inspection. Likewise, most of the subsequent CAIPP developments were also directed towards CMM-based inspection: probe accessibility and orientation for prismatic parts (Jackman and Park 1998); optimum determination of measuring points and the associated paths, pre-hit distance, and probe collision prevention. (Fan and Leu 1998); quick turnaround cell (QTC) inspection planner based on a feature based part model (Albuquerque *et al.* 2000), etc. In contrast, the present paper is mainly directed towards dimensional inspection using conventional metrological equipment.

Every dimensional inspection operation involves probing the pair of faces that makeup the dimension. The faces to be probed may be planar, cylindrical, or complexly curved. The face pair to be probed may be called an 'inspection feature'. Clearly, an inspection feature is a sub-class of a geometric feature.

The selection of the surfaces to be probed is an important step in CAIPP. However, all the seven basic types of systems identified in (Juster *et al.* 1994) had needed the user to specify each and every face needed to be probed during inspection, so the systems were far from being automated. This observation prompted Juster *et al.* to develop a method capable of automatically selecting measuring surfaces for CMM-based inspection. However, the method was applicable only to machined part features that have been duly recorded and controlled. In contrast, the present paper describes an algorithmic approach to inspection feature recognition directly from a CAD model.

As with any process planning domain, automated geometric feature recognition (GFR) is an essential requirement of CAIPP. The problem of GFR (particularly with regard to parts composed of polyhedral and cylindrical features) has attracted a great deal of attention of over the last three decades. Many of the initial works were inspired specifically by the desire to identify machining features (Grayer 1977, Woo 1982, Choi *et al.* 1984, Henderson 1984, Milacic 1985, Joshi and Chang 1988). Subsequently, researchers started venturing beyond the machining domain into, casting (Stefano 1997), plastic injection moulding (Fu *et al.* 1999), etc. Some sought to solve the problem purely in the geometric domain and in a manner applicable to any process domain (Wong 1992, Venuvinod and Yuen 1994, Venuvinod and Wong 1995, Yuen 1999, Yuen and Venuvinod 1999). GFR methods prior to (Yuen 1999) had involved only the root faces in the definition of a geometric feature. Yuen extended the approach to involve boundary face information too. This was done with the aid of multi-attributed adjacency graphs (MAAG), which represented an extension of the attributed adjacency graphs (AAG) proposed earlier in (Woo 1982).

Notwithstanding the extensive literature available on feature recognition, interestingly, there have been very few works specifically directed towards the identification of inspection features. An exception is the CAIPP work reported in (Juster *et al.* 1994) that utilized a 2-dimensional feature relationship graph. While going well beyond, the present paper utilizes a similar but simpler approach.

Our approach is designed to work within the environment of the generic computer-aided process planning support system (GCAPPSS) proposed recently by our team (Yuen *et al.* 2003)— see Figure 1. A key feature of GCAPSS is the generic object information system (GOIS) organized into five hierarchically organized layers (see Figure 2). The main features of GOIS are summarised in the Appendix.

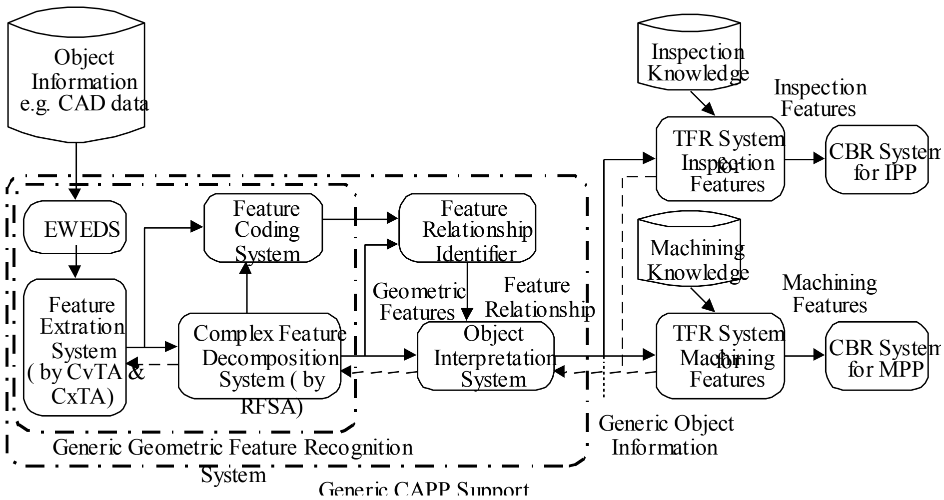

Figure 1. The GCAPPSS of (Yuen *et al.* 2003).

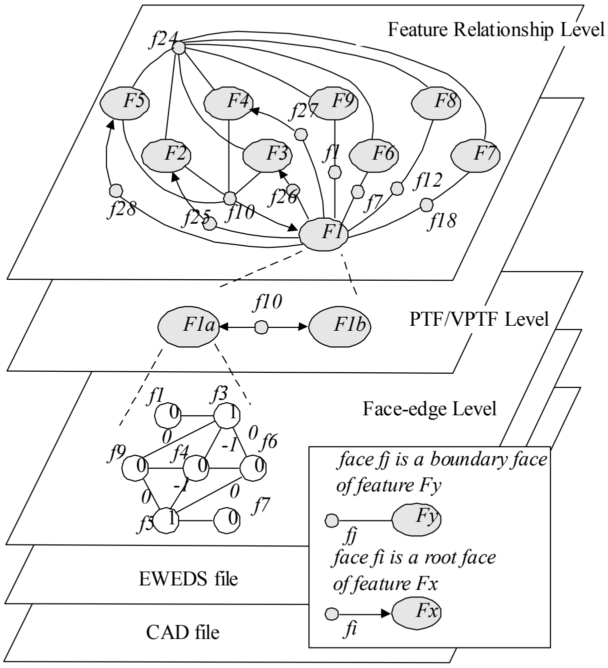

Figure 2. A GOIS (for the part shown in Figure 3).

An advantage of the GCAPSS environment is that, instead of treating each CAPP domain (machining, inspection, etc.) independently, it adopts GFR as its front-end core process, so issues related to particular process domains can be individually addressed in later stages. This strategy enables expandability while avoiding redundancies. However, while the process of recognizing a given geometric feature may be largely technology independent, the process of *what* specific features need to be recognized is essentially process-dependent. For instance, features of interest in machining-CAPP can be different from those in inspection-CAPP. Therefore, we focus on the characterization of inspection features and the development of a method for automated extraction of inspection feature from the particular viewpoint of dimensional inspection of prismatic parts with polyhedral and cylindrical features. We will also address certain problems arising from inspection feature explosion in practice. Our proposed solutions are essentially algorithmic in nature. We will illustrate our algorithms with the aid of the 'test part' (a setting gauge) shown in Figures 3 and 4.

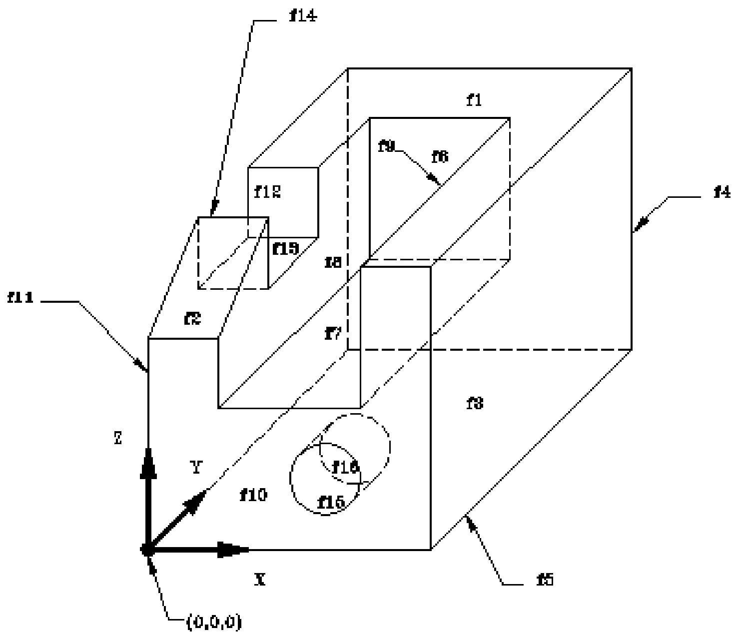

Figure 3. The 'test part' (a setting gauge) used for illustrating our algorithms.

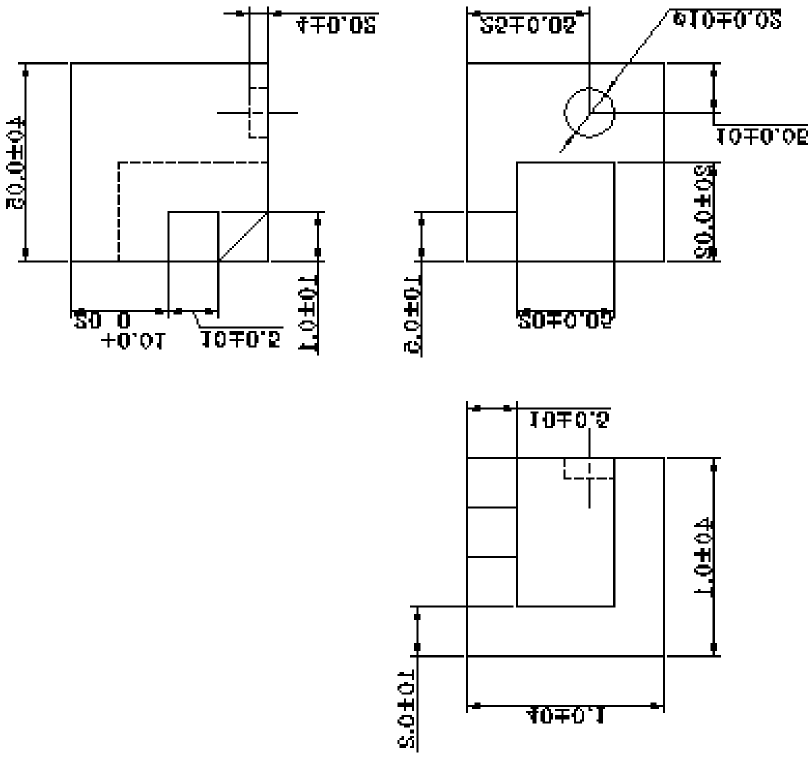

Figure 4. Orthographic views of the test part (all dimensions in mm).

2. Dimensional Inspection

The goal of dimension inspection of a given part is to evaluate the degree of conformance of the part with the specifications contained either explicitly or implicitly in the computer model(s) or drawing(s) supplied by the individual or team designing the part. Inspection necessarily involves a set of measurement processes where each process is directed towards an individual measurand in dimensional quantity. The fundamental dimensional quantity is expressed in units of length. The meter is the basic unit of length in the International System of Units (SI).

Dimensional inspection is a measurement process where the measuring equipment in the form of a probe contacts a set of faces in a specified sequence. The nature of the contact may be mechanical (micrometers, callipers, dial gauges, height gauges, etc.), pneumatic (bore gauges, ring gauges, comparators, etc.), optical (optical comparator, tool makers' microscope , measuring microscope, etc.), sonic, electro-magnetic, and so on.

Experience shows that dimensional inspection operations applicable to parts with prismatic and cylindrical features may be classified into the following cases:

Case 1 Measurement of the distance between two parallel faces: length, width, gap, slot, fin, height, protrusion, depth, recess and thickness. The actual process depends on the shape, size and orientation of the pair of faces of interest.

Case 2 The diameter of a complete cylinder/hole.

Case 3 The diameter or radius of a partial cylinder /hole or a cylindrical face.

Case 4 The distance between a cylinder/hole and a parallel face.

Case 5 The distance between two cylinder/hole.

Case 6 A combination of the above.

The measurement process in all of the above cases involves probing of faces of interest during the stage of data acquisition. A wide range of measuring equipment and length standards may be used during this stage.

4.1 3. Dimensional Inspection Features

Dimensional inspection features in prismatic parts can be of three basic types: *external*, *internal*, and *offset*. The GOIS presented in Figure 2 (Yuen 2000) possesses all the information necessary for extracting the above three types of features.

An *external inspection feature* is a pair of faces whose face normals are directed away from material side taken from any points on the faces are parallel but are directed away from each other. For example, the face-pair f12/f4 forms an external inspection feature. This conclusion is easily arrived at by reasoning over the enhanced winged data structures (EWEDS) of the two faces, which are face 4:: face(face-no(4),first-edges([-1]),"plane",[[0,1,0,-40],[0,1,0]]), and face 12: face(face-no(12),first-edges([-9]),"plane",[[0,1,0,-20],[0,-1,0]]).

An *internal inspection feature* is a pair of faces whose normal vectors of the faces directed away from material side taken from any points of the faces are parallel, but are directed towards each other. For example, the face-pair f12/f14 forms an internal inspection feature.

An *offset inspection feature* is a pair of faces whose normal vectors directed away from material side taken from any points of the faces are directed similarly. For example, the face-pair f1/f7 forms an offset inspection feature.

Other instances of these three types of inspection features in the test part are shown in Figure 5. Some important details concerning the classification of inspection features will be presented in section 8.

Clearly, the question of inspection feature classification arises only if the features have already been identified. The next section addresses the problem of inspection feature extraction from the CAD model of a part.

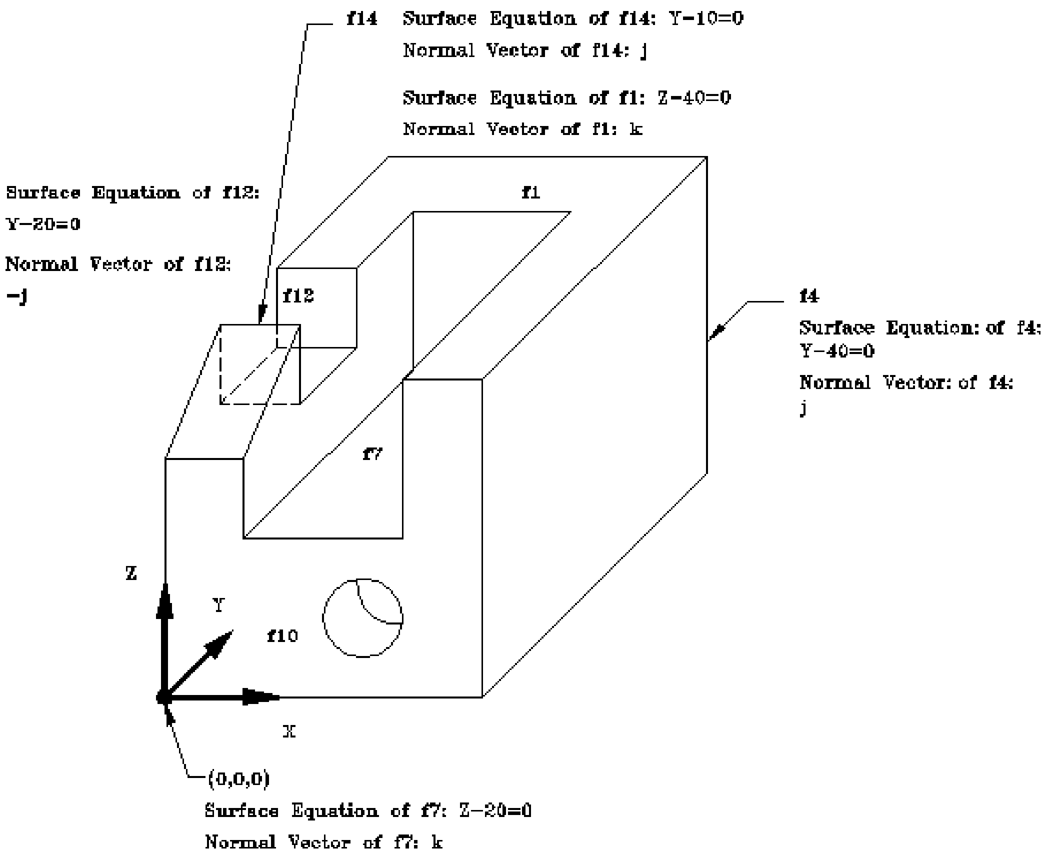

Figure 5. The major inspection features of the setting gauge.

4. An Algorithmic Approach to Inspection Feature Recognition

The GOIS provides an informal standard format for the representation of a part database in different application modules of a CAPP system. In the GOIS, the plane of a face is defined by its own parametric equation (or, its normal vector). However, the description of an inspection feature solely in terms of its pair of probing faces is inadequate for the purpose of inspection process planning. It is important to note that each of the probing faces occupies a finite area that is determined by its boundary faces. The pair of probing faces merely constitutes the *root inspection feature*. It is useful to complement this by extracting the *boundary inspection feature* too. Further, once extracted, these sub-features need to be indexed and labelled appropriately.

The following syntax is adopted in the present work for specifying an inspection feature: *Inspection-feature (Inspection-feature-ref-No.,Inspection-feature-class, FaceList-of-the-Two-Measuring-Faces, Face-List-of-the-Boundary-Faces-of-the-First-Measuring-Face,Face-List-of-the-Boundary-Faces-of-the-Second-Measuring-Face).*

The following explanations should be useful. The *first measuring face* may serve as the datum face during probing, setting and alignment. For instance, if measurement is to be performed by the aid of a comparator, the first face may be used for the 'zero' setting. Alternatively, it may be used for seating the anvil of a depth gauge. The *second measuring face* can then be taken as the *target* face during probing. A *Face-List-of-the-Boundary-Faces-of-the-First-Measuring-Face* consists of a list of boundary faces of the *the-First-Measuring-Face.* The boundary faces determine the location system, the supporting method, alignment method, other constraints, .etc. A *Face-List-of-the-Boundary-Faces-of-the-Second-Measuring-Face* consists of a list of boundary faces of *the-Second-Measuring-Face.* The boundary faces determine the accessibility of the probe or measuring head and its path, fixturing, alignment method, other constraints, etc.

A technique based on a new concept called the Multi-Attributed Spatial Graph (MASG) is now proposed to facilitate the extraction and recognition of an inspection feature. MASG is an enhancement of the Multi-attributed Adjacency Graph (MAAG) (Wong, 1992; Patri and Wong 1995) where both the nodes and arcs may have specified attributes. For instance, in a MAAG, the node attributes may be specified as *pl* for plane, *cyl* for cylindrical, etc., and the arc attributes may be specified as 0 if the edge is concave (i.e., the material-side angle, θ, between the two faces intersecting at the edge is greater than 180^o within a user-specified limit), 1 if the edge is convex ($\theta<180^o$), and 2 if the edge is smooth ($\theta = 180°$). However, so far (Wong, 1992;,Venuvinod and Wong 1995, Yuen, 1999, Yuen et al. 2000), the concept of MAAG has been applied only to pairs of adjacent faces, i.e., to face pair actually intersecting to produce a real physical edge. However, the probing faces of an inspection feature may not always have a physical edge of intersection. Hence, it is necessary to extend the notion to pairs of non-adjacent faces. MASG is created mainly with this intention.

A MASG extends the corresponding MAAG to include relationships between disjointed (non-adjacent) faces. In particular, non-adjacency is indicated by a negative arc attribute. Thus, MASG retains the list of nodes and attributes included in the

MAAG. However, the following additional arc attributes are allowed in a MASG: *–1* if the pair faces would result in a (virtual) concave edge when suitably extended, *–2* if the virtual edge is concave, *-3* if the virtual edge is smooth, *-4* if the virtual edge has $\theta = 0°$, *-5* for a pair of disjoint external parallel faces, *–6* for a pair of disjoint internal parallel faces, *–7* for a pair of disjoint offset parallel faces, -8 for a pair of disjoint faces produced by slicing a face by depressed features or faces, -9 for a pair of disjointed faces produced by separation of the face by protruding features or faces, -10 for a pair of disjoint faces produced by splitting of a face by a combination of depressed features (or faces) and protruding features (or faces), -11 for a pair of disjoint faces which have same surface but having different half-space on the material side separated by depressed features or faces, -12 for a pair of disjoint faces on the same surface but having different material-side half-spaces separated by protruding features or faces, and -13 for a pair of disjointed faces on the same surface but having different material-side half-spaces separated by a combination of depressed features (or faces) and protruding features (or faces). The MASG of an internal inspection feature (feature no. 34) in our test part is shown in Figure 6. Based on the formal syntax adopted for the coding an inspection feature, this internal feature can be coded as *inspection-feature (34,'internal',[12,14],[1, 11,13,8],[8,2,11,13]).*

Thus, MASG is capable of representing almost all possible spatial relationships between a pair of faces. In the machining domain, information concerning adjacent faces is of particular importance. In the case of dimensional inspection, our interest is mainly directed towards pairs of disjointed faces. MASG is capable of supporting the extraction of inspection features to linear as well as angular dimensional measurement. This versatility of MASG makes it particularly suitable for the implementation of the feature recognition phases in diverse CAPP domains.

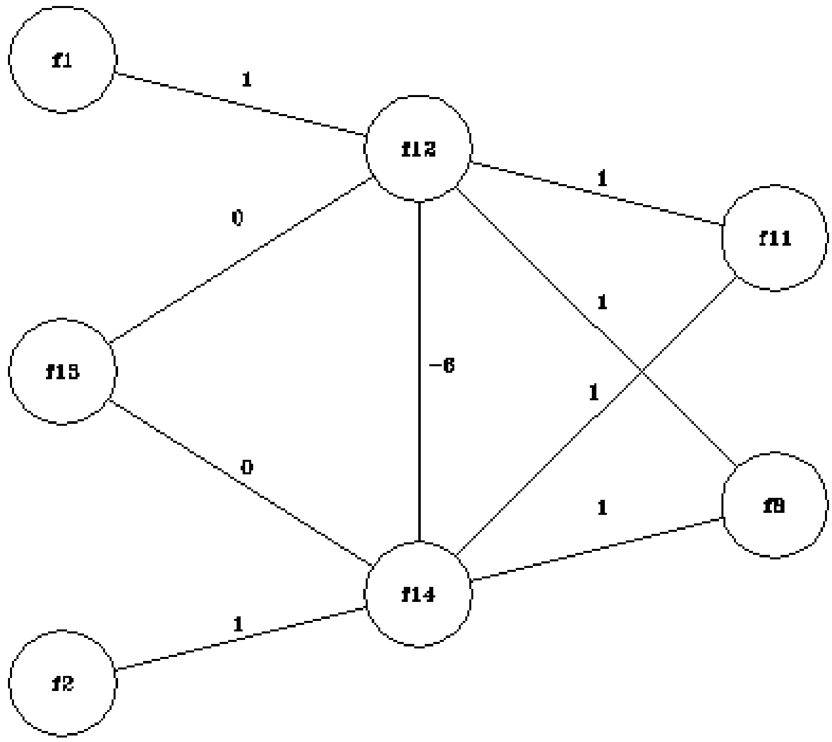

Figure 6. MASG of an internal inspection feature of the setting gauge.

The formal inspection feature representation presented here provides a basis for automation of inspection process planning. The datum/target faces and inspection feature class of an inspection feature provide the ground for selection of inspection equipment and the method of application of the equipment. The boundary face list of the respective measuring face provides the constraints for access, location, alignment and handling respectively of the measuring face.

Note that, in the context of the above inspection feature, it is immaterial during probing whether we choose f12 or f14 as the datum face (with the other face as the target face). However, not infrequently, the choice can turn out to be critical. To illustrate, consider the offset inspection feature of our test piece (Figure 3) that has f1/ f7 as the root inspection feature. The MASG of the offset inspection feature is shown in Figure 7. The following clause captures the basic information of this feature: *Inspection-feature (3, 'offset', [1,7], [3,4,11,12,10,9,6,8], [10,9,6,8]).* Now, suppose that we take f1 as the datum face for alignment, datum and tool setting. Since the dimension to be measured is a 'depth', we may use a depth gauge as the measuring instrument.

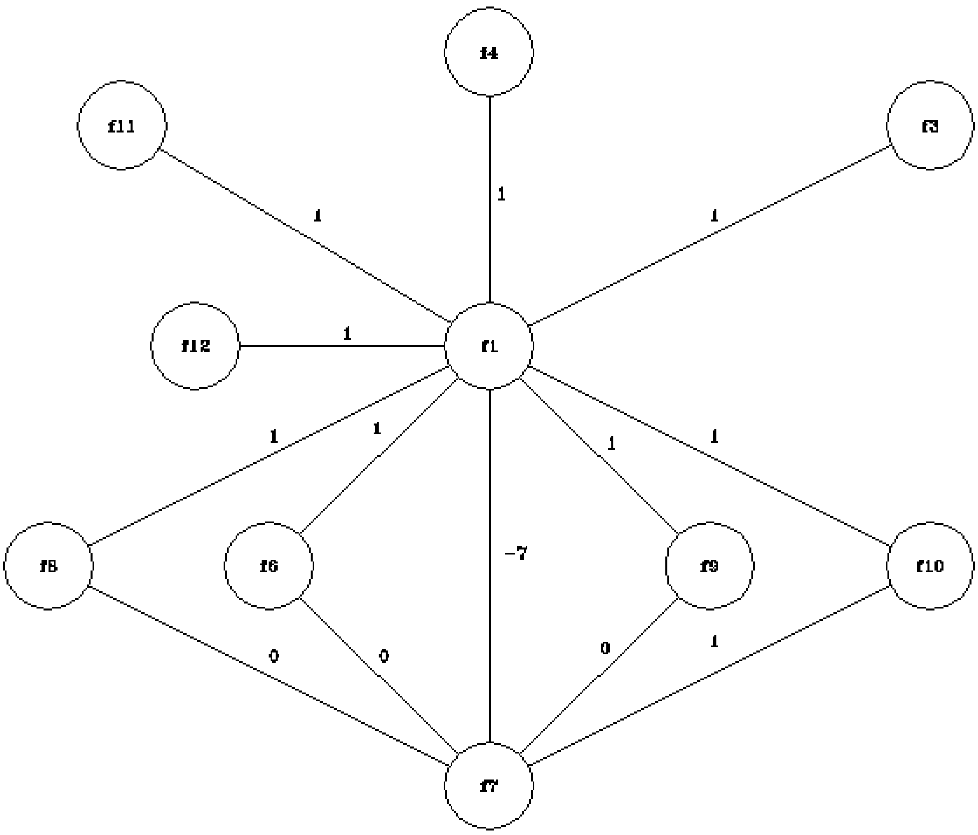

Figure 7. The MASG of an offset inspection feature of the setting gauge

In contrast, if we take f7 as the first measuring face (datum), the same inspection feature would be coded as *inspection-feature (3, 'offset', [7,1], [10,9,6,8], [3,4,11,12,10,9,6,8])*, so we would have to use a 'height gauge' for measurement. Thus, in general, different choices of the first face could lead to completely different inspection process plans, measuring equipment, and measurement data. This observation leads to the following principle: *An inspection feature, X, is the image of another inspection feature, Y, if the first measuring face of X is the same as the second measuring face of Y, and vice versa.*

5. Inspection Feature Image and Its Applications

For an inspection feature composed of two different faces, there exists a unique inspection feature *image*. (Note that there exists no image for an inspection feature formed by a cylindrical face itself.) To an inspection process planner, the existence of images suggests the possibility of adopting alternative inspection approaches. During the preparation of the process plan for an inspection feature, the planning of its own inspection feature image, if it exits, needs also to be taken into consideration. The process plan for the inspection feature may be selected through a comparative evaluation of the process planning performance measures corresponding to the inspection feature and its own image. Interestingly, this idea leads to the possibility of using a frame-based knowledge-based system (KBS) that is capable of including the following information: the measurement equipment and its application, the inspection image; the datum and target faces of the equipment; the upper and lower limits; and the associated range, resolution and instrument errors. Thus, the 'knowledge' concerning a micrometer may be captured as follows in the KBS:

```
/* Inspection Equipment Database*/
 /* Equipment: micrometer*/,
equipment("micrometer"):-
```

equip-information(application('external')),

equip-information(image('external', 'micrometer')),

equip-information(datum-face('fixed-jaw'),

equip-information(target-face('movable-jaw')),

equip-information(u-limit(25)),

equip-information(l-limit(0)),

equip-information(resolution(0.01)),

equip-information(error(0.005,10)).

equip-information(error(0.008,25)).

6. Algorithm for Inspection Feature Recognition

We are now able to write the algorithm for inspection feature recognition as follows in pseudo-code: *Begin. Input GOIS file of the part. Store the GOIS file in database.Read EWEDS from database. Determine no-of-faces For each face, extract face type, identify face types, evaluate spatial relationship with every other face, and construct spatial-rel-of-face. If the face type is 'cylindrical' identify it as 'second measurement face' to create' root inspection feature' and ' type of inspection feature' else identify the second measurement face to create ' root inspection feature' and' type of inspection feature'. For each root inspection feature, build 'Face-list-of-the-*

Boundary-Faces-of-the-First-Measuring-Face' and Face-list-of-the-Boundary-Faces-of-the-Second-Measuring-Face'. Create inspection feature. For each inspection feature without a label as image-of-inspection feature, find and label image-of-inspection-feature. Sort inspection feature and image-of-inspection feature in pairs. Renumber the inspection features. End.

7. Knowledge-based 'Filters' in Inspection Process Planning

Suppose that the above algorithm has recognized n dimensional features for inspection. Let n_c be the number of cylindrical features out of the n features. If every one of the n dimensional features were to be inspected, the complete inspection plan for the part would consist of n inspection processes. More importantly, there are $(n- n_c)$ polyhedral inspection features each of which will have an image of its own. As a result, the n inspection processes can be organized in $n\ [_{(n-nc\ )}\mathrm{P}_{(n-nc)/2}]$ ways.

With a view to appreciating the magnitude of the problem at hand, consider the results obtained from the application of our inspection feature recognition algorithm to the test piece shown in Figure 3. In this case, our algorithm (implemented in PROLOG) automatically identified 63 inspection features in the test part of which one is cylindrical, so n=63 and n_c=1. This means that, although the part has just 16 faces, there are 63 * ($_{62}\mathrm{P}_{31}$) = 4.654283 x 10^{17} different ways of organizing the inspection process plan! In practice, it is not uncommon to encounter parts with hundreds of faces. Clearly, the problem is intractable if a purely algorithmic approach were to be pursued. Of the enormous number of possible inspection plans, we need to select the most desirable single process plan based on a variety of technological and practical considerations. This would require us to draw upon much technological knowledge and human expertise.

One way of resolving this issue is to apply a suitable knowledge-based technique to subject the n individual inspection processes to a series of 'filters'. Each of these filters needs to be domain and application oriented and can be designed to trap a specific class of *'necessary-to-inspect'* inspection features. At the beginning, all the inspection features in the inspection feature database will go through each filter one by one in series. Once an inspection feature is trapped by any one filter during the filtering process, it will be retracted from the *inspection feature* database without proceeding to the next filter and is immediately input into the *necessary-to-inspect inspection feature* database. After the filtering process all these are retracted from the *inspection feature* database and stored in the *necessary-to-inspect inspection feature* database. The inspection features in the database are the inspection features selected for final inspection process planning.

The following eleven filters seem are of general importance to inspection (they may also be useful in other application diomains).

(i) (i) Product specifications filter: The specifications of a part provide the information necessary for a process planner while making inspection decisions. International Standard (ISO 406) specifies the indication of the components of linear dimension by standard tolerance symbols, permissible deviations, limits of size in one dimension (if a dimension needs to be limited in one direction only), etc. It also sets out methods for the indication of tolerances on drawings of assembled parts. The standard provides the means for identifying toleranced dimensions of individual parts as well as assembled units. Usually, the product model itself includes the tolerances on features, e.g., as in STEP (Standard for the Exchange of Product model).

(ii) Domain filter: The domain of application of a part demands special attention be given to certain dimensional inspection features. For example thickness is an important inspection feature of a plastics bag.

(iii) Application filter: The application could be a critical factor sometimes. For example, the outside diameter of the spool of a direction valve is likely to be closely inspected. In contrast, the diameters of the reservoir grooves are unlikely to be important.

(iv) General practice filter: Some dimensional features need not be inspected once the tooling has been approved, e.g., the size of a label, and the wall thickness of a preapproved plastic part, but some features are important and must be inspected, e.g., external size of a label plate to be stuck on to the front panel of a consumer electronic product.

(v) Trade practice filter: Sometimes, there are certain tolerance or accuracy requirements pertinent to a particular trade domain. For instance, ISO 2768 specifies the general permissible machining variations in dimensions without tolerance indication. All dimensions indicated on a drawing of a machined part should, in principle, be associated with tolerance data normally indicated on the dimensioning line after the nominal dimension.

(vi) Process capability filter: If it is known in advance that the manufacturing processes leading to particular class of critical dimensions are not well controlled, one does need to inspect that class of dimensional features.

(viii) Role/task filter: Some dimensional features that are critical in the context of the role and task performed by the part will require special attention and inspection. For example, the size of a shaft might need to be produced to a desired diameter in order to match the bore of a journal bearing.

(ix) Special attention filter: Engineers learn from past experience. Some dimensional features with previous failure records should draw special attention and need inspection. Sometime the customer may demand that special attention be paid to some dimensional inspection features that needs inspection, e.g., a special inspection program for a particular hole of a metal chassis might be required due to frequent problems found in the size of a particular hole during assembly of a self-tapping screw.

(x) Customer filter: Different customers may have different requirements for the same product or part depending on its application, operation environment, safety requirements, etc. For example the importance on the tolerance of the wall thickness of a plastic panel for AC-powered product is different from that of a DC-powered product due to safety requirement.

(xi) User (manual) filter: For some products, the sizes and quality constraints could be varied to suit different market sectors, e.g., those for German versus the Chinese markets.

8. Implementation and Testing

The authors have written an automatic feature recogniser in PROLOG to implement the above algorithm. Each dimensional feature along with its inspection feature image, if it exists, is extracted automatically. 63 inspection features of the setting gauge shown in Figures 3 and 4 were extracted automatically from the feature recognition.

A noteworthy point here with regard internal and external inspection features. The solid angle between two faces f_i and f_j of a prismatic part is obtained by

$\Phi_{(i,,j)}= \cos^{-1}(N_i \bullet N_j)$, in which N_i and N_j are the unit normal vectors of the faces directed away from the material side. Thus, the dot product, $N_i \bullet N_j$, for face pair f12/f4 that forms an external inspection feature. However, the same is true for the internal inspection feature formed by the face pair f12/f14. This means that one is unable to distinguish between internal and external inspection features. But, such distinction is of great importance in inspection planning. In solving this problem, we have found the following algorithm to be effective:

/* Algorithm for distinction between internal inspection feature and external inspection feature */ *Begin. For each measuring face of an inspection feature composed of two measuring faces f_i and f_j, select one reference point on the face. For each measuring face take a selected reference point as the start point 'S' of the normal unit vector of the measuring face directed away from the material side of the face and the end point of that normal vector established be 'E'. Label an inspection feature composed of two measuring faces f_i and f_j as an 'external inspection feature'* ***if*** *$N \bullet N_j .= -1$ and distance(S_i,S_j) > distance(E_i,E_j). Laber an inspection feature composed of two measuring faces f_i and f_j as an 'internal inspection feature' if $N_i \bullet N_j .= -1$ anddistance(S_i,S_j) < distance(E_i,E_j).End.*

Several filters have been implemented by the present authors to cover parts such as that shown in Figure 3. The filters were developed in the form of production rules implemented in PROLOG. For instance, a rule for the '"Product Specification Filter' is as follows: *An inspection feature is necessary to inspect if its tolerance zone is smaller than* $\pm 0.2mm$.

When applied to the part in Figure 3, the above filter yielded just 17 necessary inspection features including the corresponding inspection feature images. Of these, 8 were external, 3 internal, and 6 offset.

9. Conclusion and Suggestions for Further Work

Amongst the various CAPP domains, notwithstanding its enormous importance in industry, non-CMM-based inspection process planning has attracted very little research effort so far. The present paper has tried to partially fill this gap by addressing two basic issues: inspection feature representation, and inspection feature recognition. In particular, how dimensional inspection features could be characterized using Multi-Attributed Spatial Graphs (MASG) has been described. Algorithms for inspection features have also been developed. A series of domain-specific and knowledge-based filters have been proposed to contain the problem of inspection feature explosion and enable automatic selection of end user-oriented dimensional inspection features. In particular, two basic issues related to CAIPP have been addressed: identifying and recognizing the dimensional inspection features, and identifying and recognizing the associated dimensional inspection constraints for the inspection features.

A logical next step is to investigate methods capable of generating, in as automated a manner as possible, appropriate dimensional inspection methods corresponding to at least the inspection feature commonly found in industrial practice. The second step is to develop a methodology to integrate all the dimensional inspection methods of individual inspection features to generate an overall inspection process plan for a given part. This would involve optimisation of the sequence of inspection operations.

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Appendix: Generic Object Information System (GOIS)

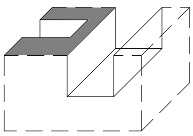
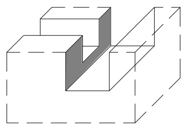
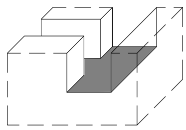
The *generic object information System* (GOIS) provides the CAD model data including detailed geometric data, topological information, *primitive template features* (PTF) and variations of PTFs (VPTF).

Level 1 (Feature Relationship level) consists of feature-face graph (FF graph) of the part. The nodes are features. An arc between two nodes is the connecting face between two features. The arcs have a smaller node called a 'connecting face node' that records the properties (including fine data such as the dimensions) of the connecting faces. Faces composing a feature can be classified into two types: 'Root' or 'Boundary (B)'. To reduce the visual complexity, common connecting face nodes are merged. In the test part, f24 is the boundary face (B) of features 2, 3, 4, 5, 6, 7, 8 and 9. Feature relationships are established through three types of feature interactions: RB, RR, and BB (see Table 1). The implementation of this approach results in relationship 1 in Figure A1 being coded as *feature-rel.(1, 1,'blind_slot', 8, 'RB', 2, 'slot').*

Level 2 (PTF/VPTF level) contains the feature MAAG corresponding to each decomposable feature in the first layer. Since this layer is designed for further representation of a decomposable feature in the first layer, pointers are established to the appropriate features in the first layer. The nodes in this layer represent the PTFs or VPTFs that have been identified by using appropriate decomposition methods for the complex features. This results in features 1 and 2 being coded as follows: feature(1, 'blind-slot'", [8,6,9,7],[1,10,2,13,12]), and feature(2, 'slot', [12,13,14],[1,8,2,11]).

Level 3 (Face-edge Level) contains the coarse data information of the part in the form of a MAAG. The relevant 'coarse' information concerning the faces is whether the face is plane ('pl'), cylindrical ('cyl'), etc. The coarse information concerning an edge refers to whether the edge is concave (0), convex (1), smooth (3), etc. The following syntax is used in describing information at this level. This results in the relationship between faces 1 and 4 being coded as adj(1 ,"pl",1,4,"pl")

Table A1 Three basic types of feature interactions

BB Interaction The two features have common boundary face(s)	**RB Interaction** The boundary face of one feature is the root face of the other	**RR Interaction** The two features have a common root face
		

Level 4 (EWEDS level) contains the Extended Winged Edge Data Structure (Wong 1992; Venuvinod and Wong 1995) of the part. This data structure explicitly lists the attributes of each edge, vertex, and face using the following syntax:

Level 5 (CAD Level) contains the CAD file of the part in a neutral data format that is readable by any computer system.