4

Computer-Aided Design

Geometric modeling is the first step in the computer-aided engineering (CAE) analysis of a designed product. The objective is to encapsulate all geometric data pertaining to the part in a single model and specify all necessary material properties as additional information. In this context, solid modeling, as a branch of geometric modeling, refers to the geometric description of solid objects in their entirety. Solid models (1) must be complete: the graphical model must not be an ambiguous representation, (2) must have integrity: operation on geometric models must preserve integrity, such as maintaining the connection of edges at a point when it is moved, and (3) provide accuracy in modeling of complex shapes.

Solid modeling is a multifaceted operation. At the forefront, a user describes a geometric model, through a graphical representation, to the computer, which in turn stores this representation, in one format or another, and furthermore allows the manipulation of this representation through a set of mathematical transformations/operators/etc. Thus a user of a computer-aided design (CAD) system for solid modeling purposes should have a basic knowledge of computer graphics principles needed for the manipulation and storage of graphical data.

As a preamble to solid modeling, this chapter will first review geometric modeling principles and concepts in Sec. 2 and then address the topics of solid modeling techniques, feature-based design, and product-data exchange standards in Sec. 3 to 5.

4.1 GEOMETRIC MODELING—HISTORICAL DEVELOPMENT

Sketchpad is known as the first graphical user interface (GUI), developed at M.I.T. by I. E. Sutherland, capable of interpreting information sketched on a computer display monitor. The software was developed during the period 1960 to 1962 on a TX-2 computer and primarily utilized a light pen (in conjunction with a push button) for data input (points, straight lines, circles, etc.). (It is interesting to note that the period was also *marked* by the development of the APT, automatically programmed tool, computer language, also developed at MIT, for the programming of numerical-control machine tools, the former in the Electrical Engineering department and the latter in the Mechanical Engineering department.)

Topological data related to an object model was stored in the computer as a "ring" structure, novel to sketchpad. When the user moved a vertex, the object geometry was be self-adjusted accordingly by the movements of the attached edges. The software was also used for basic engineering analysis operations, such as computing distribution of forces on the member links of a truss bridge.

The sketchpad system was followed by the development of DAC-1 (design augmented by computers) by General Motors in 1964 and CADAM (computer-aided design and manufacturing) by Lockheed Aircraft in 1965. The 1970s and early 1980s were marked by the development of numerous CAD systems, such as Computervision's Designer series that ran on proprietary hardware—however, only a handful of these systems survived beyond the late 1990s. Today, Pro/Engineer by Parametric Technology Corporation and I-DEAS by Structural Dynamics Research Corporation (SDRC) are the two primary CAD software packages that hold a large share of the CAD market. Both packages run on microcomputer (SUN, HP, etc.) as well personal computer platforms (IBM, Dell, etc.).

4.2 BASICS OF GEOMETRIC MODELING

4.2.1 Points and Curves

Points are the simplest geometric entities normally represented in Cartesian space by three coordinates (x, y, z). Points are also referred to as vertices when discussed in the context of bounding a line (or an edge of a surface).

Three-dimensional curves, in turn, can be represented in a parametric form, as a function of a single variable $u \in [0, 1]$:

$$x = x(u) \qquad y = y(u) \qquad \text{and} \qquad z = z(u) \tag{4.1}$$

Any point on such a parametric curve is defined by the components of the vector $\mathbf{p}(u)$. Thus the boundary conditions of a parametric curve are defined by the vectors $[\mathbf{p}(0), \mathbf{p}(1), \mathbf{p}'(0), \mathbf{p}'(1)]$, where

$$\mathbf{p}'(u) = \frac{d\mathbf{p}(u)}{du} \tag{4.2}$$

In parametric form, a straight line would be represented as

$$x = a + ku \qquad y = b + lu \qquad \text{and} \qquad z = c + mu \tag{4.3}$$

where (a, b, c) and (k, l, m) are constants. Similarly, a planar circle would be represented as,

$$x = x_c + r\cos 2\pi u \qquad y = y_c + r\sin 2\pi u \qquad \text{and} \qquad z = z_c \tag{4.4}$$

where r is the radius of the circle and (x_c, y_c, z_c) are constants. A circular arc, in turn, is represented as

$$x = x_c + r\cos u \qquad y = y_c + r\sin u \qquad \text{and} \qquad z = z_c \tag{4.5}$$

where $u \in [u_s, u_e]$—u_s and u_e represent the start and end points of the arc.

Although any curve can be represented by a corresponding parametric set of equations, in practice, several curves might have to be joined in order to achieve a specific part geometry. For such an objective, the two curves s_1 and s_2 can be manipulated in Cartesian space and joined end to end while satisfying the continuity constraint. That is,

$$\mathbf{p_1}(1) = \mathbf{p_2}(0) \quad \mathbf{p}_1'(1) = \mathbf{p}_2'(0) \quad \text{and} \quad \mathbf{p}_1''(1) = \mathbf{p}_2''(0) \tag{4.6}$$

where $\mathbf{p}'$ and $\mathbf{p}''$ are the first and second parametric derivatives, respectively. In Eq. (4.6), the first two constraints simply ensure continuity of end-to-end meeting and having identical slopes at this point, respectively. The third constraint (i.e., continuity of second derivatives), on the other hand, further ensures that the two curves have equal curvature at the joining point.

Curve Fitting

On many occasions a designer faces the task of curve fitting to a set of data points collected through experimentation. In industrial design, for example, this task would correspond to approximating a handcrafted surface by a mathematical representation, where a coordinate-measuring

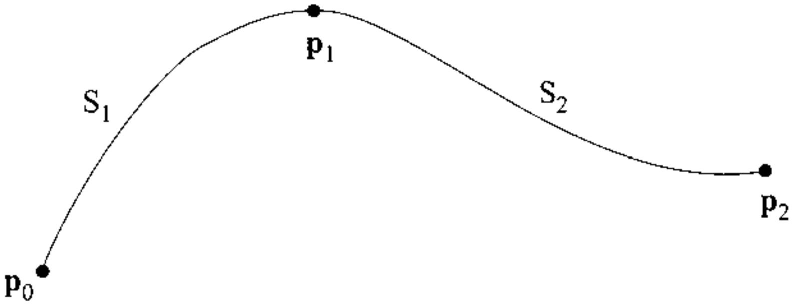


FIGURE 1 Cubic spline fit to three points.

machine (CMM) would be used to determine a sufficiently large number of points on the actual surface.

Two possible solutions to the curve-fitting problem would be the least-squares fit, where the best curve would most likely not pass through any one of the points, and the spline fit, where a set of curves would be determined that pass through all the given points and furthermore provide the designer with any desired degree of continuity at meeting points (i.e., matching higher-order derivatives), as in Eq. (4.6). In both cases, the mathematical problem at hand is the determination of the coefficients of the equations.

As an example, let us consider a cubic spline fit to three points, ($\mathbf{p}_0$, $\mathbf{p}_1$, $\mathbf{p}_2$). The designer is required to find the coefficients of two curves (both third-degree polynomials), one from $\mathbf{p}_0$ to $\mathbf{p}_1$ and another from $\mathbf{p}_1$ to $\mathbf{p}_2$. The constraints imposed on this problem (i.e., finding simultaneously the coefficients of both curve representations) are (1) the coordinates of all the three points and (2) the desired first and second derivative values at the first and last points, $\mathbf{p}_0$ and $\mathbf{p}_2$, respectively. Additionally, the solution algorithm is required to determine the curves' coefficients such that the first and second derivatives of both match at the joining point, $\mathbf{p}_1$ (Fig. 1).

The coefficients of both sets of equations, c_{ijk}, $k=1, 2$, can be described in a matrix form as

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{bmatrix} c_{111} & c_{121} & c_{131} & c_{141} \\ c_{211} & c_{221} & c_{231} & c_{241} \\ c_{311} & c_{321} & c_{331} & c_{341} \\ c_{411} & c_{421} & c_{431} & c_{441} \end{bmatrix} \begin{pmatrix} u^3 \\ u^2 \\ u \\ 1 \end{pmatrix} \tag{4.7}$$

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{bmatrix} c_{112} & c_{122} & c_{132} & c_{142} \\ c_{212} & c_{222} & c_{232} & c_{242} \\ c_{312} & c_{322} & c_{332} & c_{342} \\ c_{412} & c_{422} & c_{432} & c_{442} \end{bmatrix} \begin{pmatrix} u^3 \\ u^2 \\ u \\ 1 \end{pmatrix} \tag{4.8}$$

The above spline fit technique, though ensuring that the curves pass through all the given points and satisfy the boundary conditions, may yield curves with undesirable inflection points, especially when overly constrained (Fig. 2). In response to this problem, P. Bézier (a mechanical engineer) of the French automobile firm Renault developed the curve now known as the Bézier curve in the late 1960s.

A Bézier curve satisfies the following four conditions while attempting to approximate the given points (but not passing through all of them) (Fig. 3a). For $(n+1)$ points,

1. The curve must only interpolate the first and last control points $(\mathbf{p}_0, \mathbf{p}_\mathrm{n})$.
2. The order of the polynomial is defined by the number of control points considered, where

$$\mathbf{p}(u) = \sum_{i=0}^{\mathrm{n}} \mathbf{p}_i \, B_{i,n}(u) \tag{4.9}$$

and

$$B_{i,\mathrm{n}}(u) = \left[\frac{n!}{i!(n-i)!}\right] u^i (1-u)^{\mathrm{n}-i} \tag{4.10}$$

For example, for four control points, $n+1=4$,

$$\mathbf{p}(u) = (1-u)^3 \mathbf{p}_0 + 3u(1-u)^2 \mathbf{p}_1 + 3u^2(1-u)\mathbf{p}_2 + u^3 \mathbf{p}_3 \tag{4.11}$$

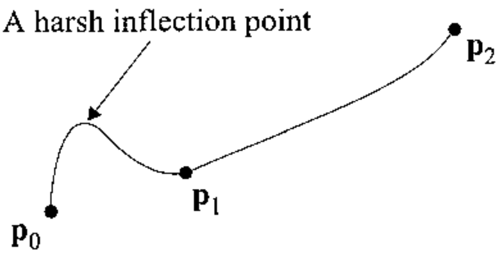


FIGURE 2 An undesirable spline fit.

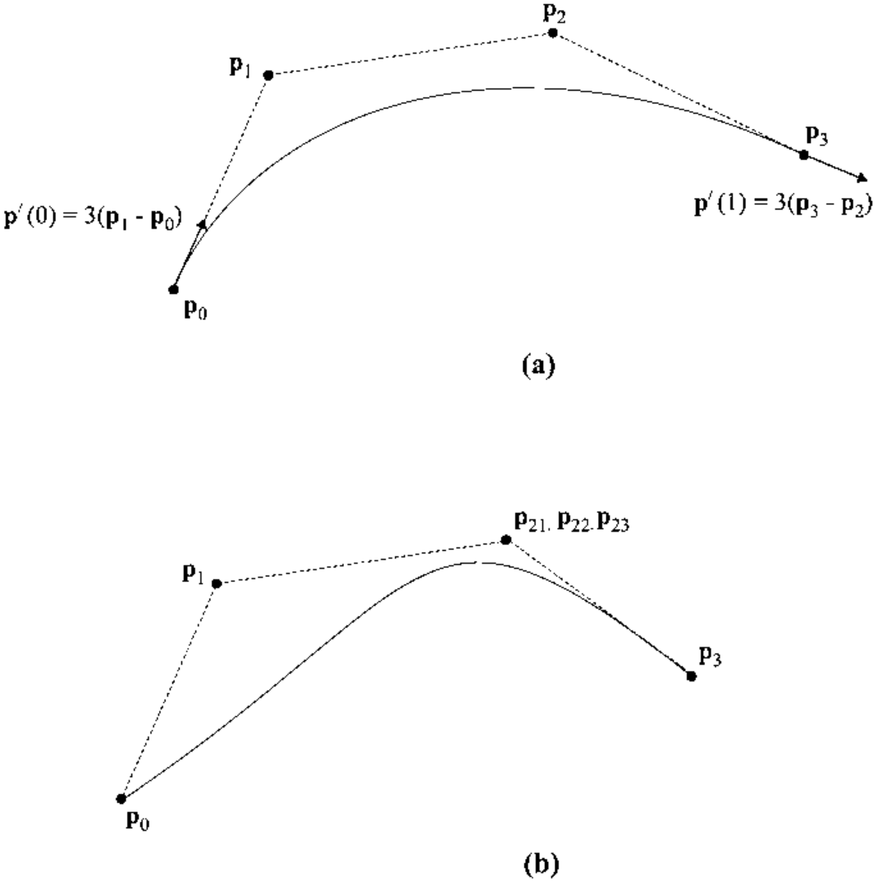


FIGURE 3 (a) Unweighted and (b) weighted Bézier curves.

where at $u = 0$, $\mathbf{p}(0) = \mathbf{p}_0$, and at $u = 1$, $\mathbf{p}(1) = \mathbf{p}_3$ satisfying Condition 1 above.

3. The curve satisfies r^{th} order derivatives at the first and last points only, where $r \leq n$ (for $n+1$ control points):

$$\mathbf{p}^r(0) = \frac{n!}{(n-r)!} \sum_{i=0}^{r} (-1)^{r-i} C(r,i)\mathbf{p}_i \tag{4.12}$$

and

$$\mathbf{p}^r(1) = \frac{n!}{(n-r)!}\sum_{i=0}^{r}(-1)^i \; C(r,i)\mathbf{p}_{n-i} \tag{4.13}$$

where

$$C(r,i) = \left[\frac{r!}{i!(r-i)!}\right]$$

The first two derivatives for a Bézier curve with four control points would be

$$\begin{aligned} \mathbf{p}'(0) &= 3(\mathbf{p}_1 - \mathbf{p}_0) \qquad & \mathbf{p}''(0) &= 6(\mathbf{p}_2 - 2\mathbf{p}_1 + \mathbf{p}_0) \\ \mathbf{p}'(1) &= 3(\mathbf{p}_3 - \mathbf{p}_2) \qquad & \mathbf{p}''(1) &= 6(\mathbf{p}_3 - 2\mathbf{p}_2 + \mathbf{p}_1) \end{aligned}$$

4. The shape of the curve can be changed by emphasizing certain desired points by creating pseudopoints coinciding at the same location. For example, for the curve shown in Fig. 3b, we fit a Bézier curve to six points, three of which coincide, thus emphasizing the importance of that specific location.

4.2.2 Surfaces

Surface modeling is a natural extension of curve representation and an important step toward solid modeling. In three-dimensional space, a surface has the following parametric description:

$$x = x(u,w) \qquad y = y(u,w) \qquad \text{and} \qquad z = z(u,w) \tag{4.14}$$

where a point on this surface is defined by $\mathbf{p}(u,w)$, and u, $w \in [0, 1]$.

If one considers a patch of surface, the four vertices of this patch, $(\mathbf{p}_{00}, \mathbf{p}_{01}, \mathbf{p}_{10}, \mathbf{p}_{11})$, are defined by their respective coordinate values as well as by the two first-order derivatives at each vertex:

$$\begin{array}{ll} \mathbf{p}^{u}_{00} = \left.\dfrac{\partial \mathbf{p}}{\partial u}\right|_{u=0,w=0} \qquad & \mathbf{p}^{w}_{00} = \left.\dfrac{\partial \mathbf{p}}{\partial w}\right|_{u=0,w=0} \\ \quad\vdots & \quad\vdots \\ \mathbf{p}^{u}_{11} = \left.\dfrac{\partial \mathbf{p}}{\partial u}\right|_{u=1,w=1} \qquad & \mathbf{p}^{w}_{11} = \left.\dfrac{\partial \mathbf{p}}{\partial w}\right|_{u=1,w=1} \end{array} \tag{4.15}$$

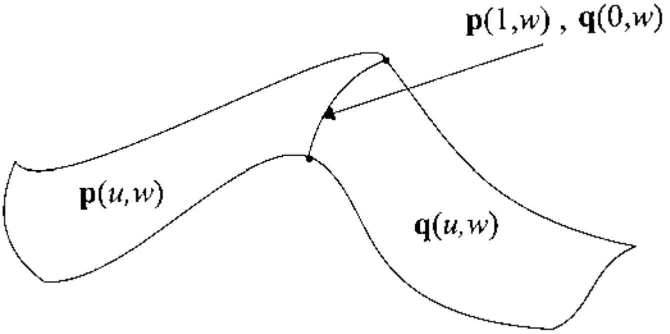


FIGURE 4 Patching of surfaces.

A unit normal vector at any point on this surface can be defined as

$$\mathbf{n}(u,w) = \frac{\left(\frac{\partial \mathbf{p}}{\partial u}\right) \times \left(\frac{\partial \mathbf{p}}{\partial w}\right)}{\left|\frac{\partial \mathbf{p}}{\partial u} \times \frac{\partial \mathbf{p}}{\partial w}\right|} \tag{4.16}$$

The unit normal is an important tool to be utilized in the geometric modeling of solids, usually required to point outward.

As in the case of curves, multiple surfaces can be patched together at their edges—that is two patches, $\mathbf{p}(u,w)$ and $\mathbf{q}(u,w)$, share a curve on each patch, for example $\mathbf{p}(1,w)$ and $\mathbf{q}(0,\mathrm{w})$ (Fig. 4)

Surface Fitting

In fitting a surface to a set of points, one can choose to carry out this operation via a number of spline-fitted, patched surfaces or by using one single "approximate surface," such as a Bézier surface. No matter what the method is, one needs to consider the first-order (and even second-order) order derivatives of the surfaces' boundary conditions.

The Bézier surface equation is defined as

$$\mathbf{p}(u,w) = \sum_{i=0}^{m}\sum_{j=0}^{n} \mathbf{p}_{ij} B_{i,m}(u) B_{j,n}(w) \tag{4.17}$$

where $\mathbf{p}_{ij}$ are the $(m+1)\times(n+1)$ control points, $B_{i,m}$ and $B_{j,n}$ are defined as in Eq. (4.10), and $u,\ w \in [0,\ 1]$. As in the Bézier curve case, only a limited number of control points actually lie on the Bézier surface [(e.g., the four points in Fig. 5: $(u,w)=(0,0)$, $(0,1)$, $(1,0)$ and $(1,1)$]. The remaining points control the curvature of the Bézier surface. Furthermore, as in the case of

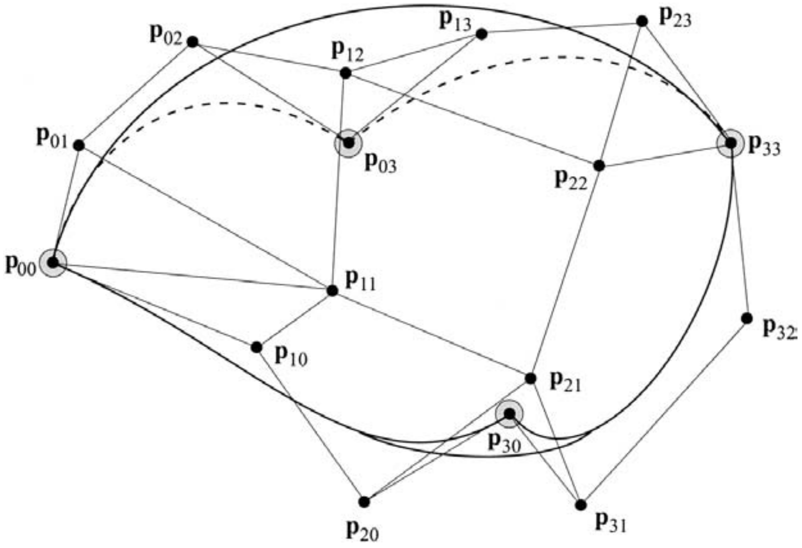


FIGURE 5 4×4 Bézier surface.

the Bézier curve, certain control points can be emphasized by creating a larger number of coinciding pseudopoints at a specific desired location.

4.2.3 Solids

Several solid modeling techniques were developed over the past two decades, three of which will be detailed below in Sec. 4.3. In this subsection, however, a brief review of pertinent issues will be addressed to provide a transition from the above discussion on surface modeling to these solid-modeling techniques.

A solid can be described as a "hyperpatch" by the parametric representation

$$x = x(u, v, w) \qquad y = y(u, v, w) \qquad \text{and} \qquad z = z(u, v, w) \tag{4.18}$$

where $u, v, w \in [0,1]$ (Fig. 6). In Eq. (4.18), fixing the value of any one of the three parameters would result in the definition of a surface that can be on or within the solid.

The simplest example of a solid is a rectangular prism obtained by substituting the proper constraints into Eq. (4.18) to yield

$$\begin{aligned} x &= a + (b-a)u \\ y &= c + (d-c)v \\ z &= e + (f-e)w \end{aligned} \tag{4.19}$$

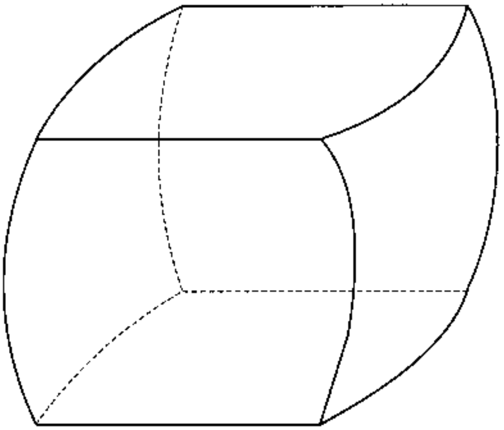


FIGURE 6 A solid.

One can note that the above equation describes points that are on the surface as well as inside the prism.

Solid models of objects must satisfy the following criteria:

Rigidity: The shape of the object remains fixed as it is manipulated in Cartesian space (i.e., translated and/or rotated).
Homogeneity: All boundaries of the model must be in contact with and enclosing the volume of the solid.
Finiteness: No dimension of the model can be infinite in magnitude.
Divisibility: The solid model must yield valid subvolumes when divided by Boolean operations.

4.3 SOLID MODELING

Computer-aided design (CAD) software packages are based on the mathematical principles of geometric modeling, some of which were discussed above in Sec. 4.2. Prior to the discussion of solid modeling techniques commonly employed by CAD systems, it will be beneficial to list briefly some of the tools that these systems utilize in manipulating curves, surfaces, and solids:

Segmentation: This is a division of a curve or a surface into several segments, while preserving the characteristics of the original entity in every one of the segments. This objective is achieved through reparameterization of the original entity.

Intersection: The intersection of two curves in three-dimensional space is a root-finding problem (for determining the coordinates of the intersection point). It is a nonlinear problem, for which numerical methods must be utilized. The complexity of the problem is increased for surface-with-curve and surface-with-surface intersections. Numerical methods developed for this purpose may follow a procedure such as the one developed by H. G. Timmer: Select one of the surfaces and create a grid structure; examine all grids for possible intersection points; trace individual intersection segments within each grid; order and connect the individual segments; and parameterize the intersection curve.

Transformation: Geometric transformation of an object may involve translation, rotation, or even scaling of its shape. Homogeneous transformation is the most efficient way of carrying out translation and rotation simultaneously—it defines the transformation of a coordinate frame attached to an entity with respect to a fixed “world” coordinate frame. It is defined by a (4 × 4) matrix,

$$T = \begin{bmatrix} R_{3\times3} & d_{3\times1} \\ 0\ 0\ 0 & 1 \end{bmatrix}_{4\times4} \tag{4.20}$$

where $R_{3\times3}$ is a square rotational matrix defining three successive rotations with respect to the world coordinate frame and $d_{3\times1}$ is the translation vector defining three simultaneous translations along the three orthogonal axes of the world coordinate frame.

Scaling: The size of a geometric entity (curve or surface) may be changed by scaling its geometric coefficients pointwise. The elements of the scaling matrix can be chosen to scale down the entity (with positive element values less than 1) or scale it up (with element values greater than 1). (Negative scaling factors cause reflection.)

Boolean operations: Set theory is an important tool in combining solid geometries (usually, simple shapes, “primitives”). The term set refers to a collection of (well-defined) objects—points in geometric modeling. Different sets can be combined, through Boolean operators, to create new sets. The three common Boolean operators are union, intersection, and complement (Fig. 7):

Union $\quad \mathrm{C} = \mathrm{A} \cup \mathrm{B}$,
Intersection $\quad \mathrm{D} = \mathrm{A} \cap \mathrm{B}$,
Complement $\quad \mathrm{E} = (\mathrm{A} \cup \mathrm{B})' = \mathrm{S} - (\mathrm{A} \cup \mathrm{B})$

The new set E above includes all the elements in the universal set, S, which are not included in A or B.

The three most common solid modeling techniques used by CAD systems are primitive instancing and sweeping, construction, and boundary representation. Decomposition models that describe solids based on a

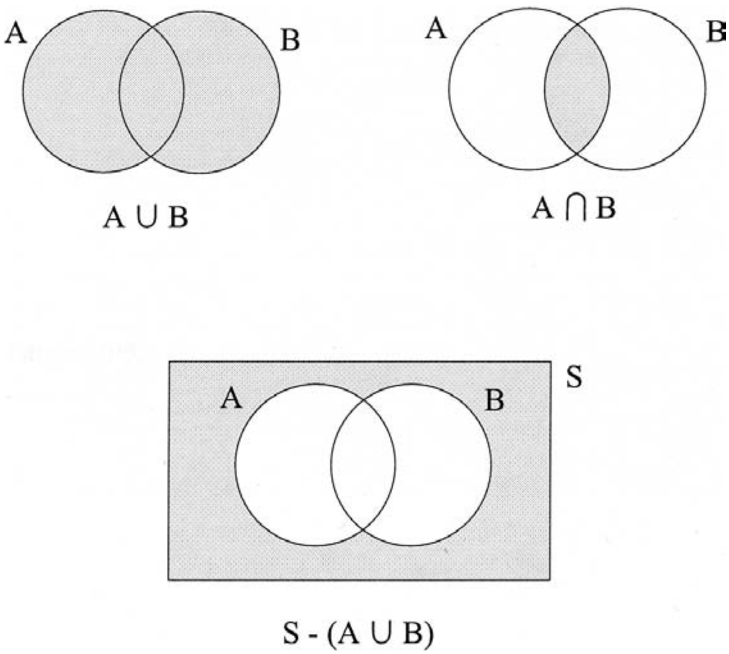


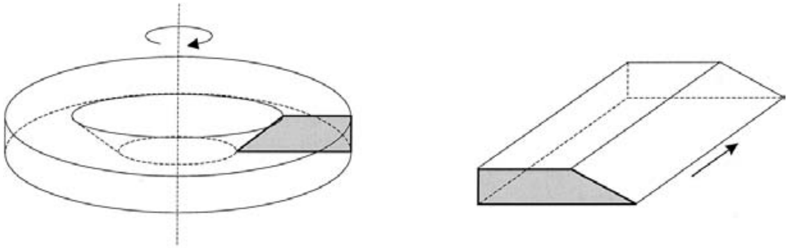
FIGURE 7 Venn diagrams of Boolean operations.

combination of geometric blocks will not be discussed in this chapter. We will, however, discuss briefly the issue of conversion of a solid representation from one model to another, for example from a constructive solid geometry model to a boundary representation model.

4.3.1 Primitive Instancing and Sweeping

Primitive instancing refers to the scaling of simple geometrical models (primitives) by manipulating one or more of their descriptive parameters, for example, elongating a cylinder, changing the dimensions of a rectangular prism, etc. As will be discussed below in Sec. 4.4, geometric primitives can play an integral role in feature-based design, where a set of (form) features are combined to generate a more complex model. It will also be shown that such primitives can be combined through Boolean operators for constructive solid geometry modeling.

Due to their simplicity, most geometric primitives can be generated by a sweeping ("extrusion") process, where a surface is either translated along spatial curve or rotated about it (Fig. 8). (The designer must be careful that



Rotational Sweep

Translational Sweep

FIGURE 8 Sweeping of surfaces.

the end result is a valid solid.) In most cases, solid geometric models generated by a sweeping operation can be converted to construction and boundary representation models.

4.3.2 Constructive Solid Geometry

Constructive solid geometry (CSG) modelers allow designers to combine a set of primitives through Boolean operations. In the background (transparent to the user), these modelers represent and store the primitives as "half-space" models—these are simple geometric models comprising point sets bounded by a surface, i.e., points in three-dimensional space are defined as belonging to the half-space or being excluded. (An example half-space model would be that bounded by a cylindrical surface extending to infinity—points thus would be on and within the volume enveloped by the surface or be on the outside.) There do exist some CAD systems, however, that allow designers to work with bounded primitives, which are indeed a collection of patched half spaces themselves.

CSG-based solid models are represented as tree (or graph) structures. The leaves of the graph are the primitives, while the nodes that connect the branches are the Boolean operations applied on the individual (leaves) primitives (Fig. 9).

Naturally, CSG modelers rely on several geometric modeling tools discussed in this chapter: properly scaled primitives must be transformed (positioned and oriented) prior to their combinations; the modeler must determine exact intersection curves between the surfaces of the two primitives to be combined, and finally the modeler must use set theory to determine the new solid model obtained.

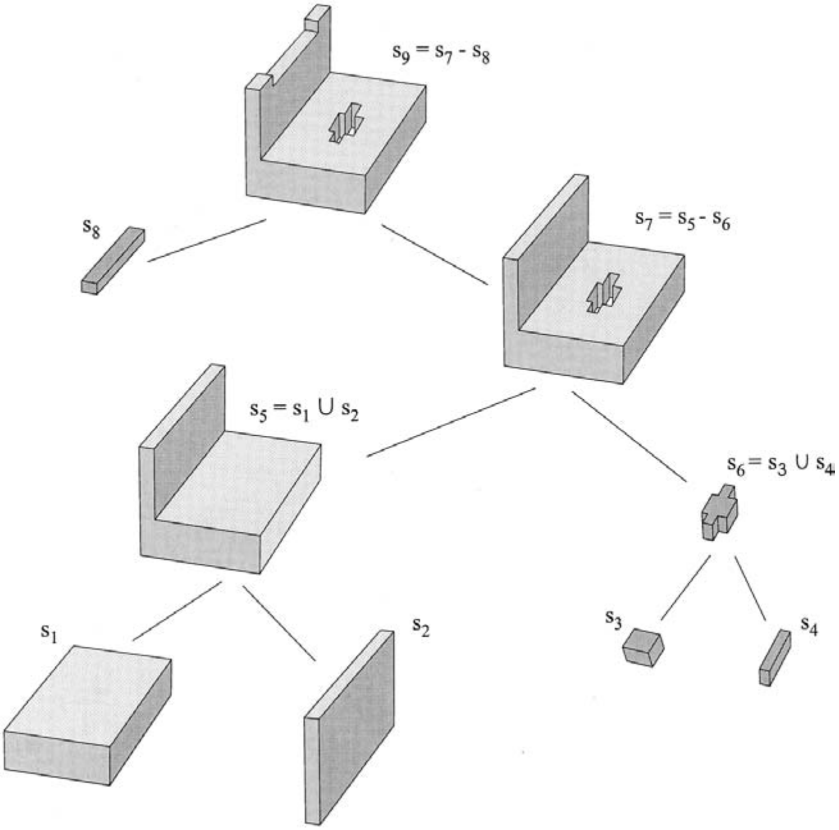


FIGURE 9 CSG model.

4.3.3 Boundary Representation

Boundary representation (B-Rep) models describe solids “topologically.” That is, they rely on the notion that all solids are bounded by surfaces. Based on this surface-oriented view, a B-Rep model comprises faces, edges, and vertices, and each face has an unambiguous mathematical representation. A face may have several inner bounding loops in addition to the outer bounding curve. For example, a surface may have the bounding loops of holes/cavities included within it. Although B-Rep is a surface-oriented model, one can easily calculate the volumetric properties of the enclosed solid through integration.

Most engineering objects have either polyhedral or curved (cylindrical or spherical) surfaces. The former are easier and more intuitive to represent via their (finite in number) vertices and connected (linear) edges (Fig. 10a). For a cylindrical object, on the other hand, the side curved surface can be represented by one edge and two vertices, whereas the two opposite (circular) planar surfaces can be each represented by one edge and one vertex (coinciding with one of the vertices of the side surface) (Fig. 10b). A sphere can be represented by one face, one vertex, but no edges.

In the formal sense, a vertex is a unique point in Cartesian space defined by three coordinates. An edge is a finite-length curve bounded by two vertices—it must be non-self-intersecting. A loop is an ordered, directed collection of vertices and edges—i.e., a boundary. A face is a finite-size surface, non-self intersecting and bounded by one or more loops. The most common B-Rep modelers structure geometric data based on edge information, where a face is represented in terms of its loops. One can go a step

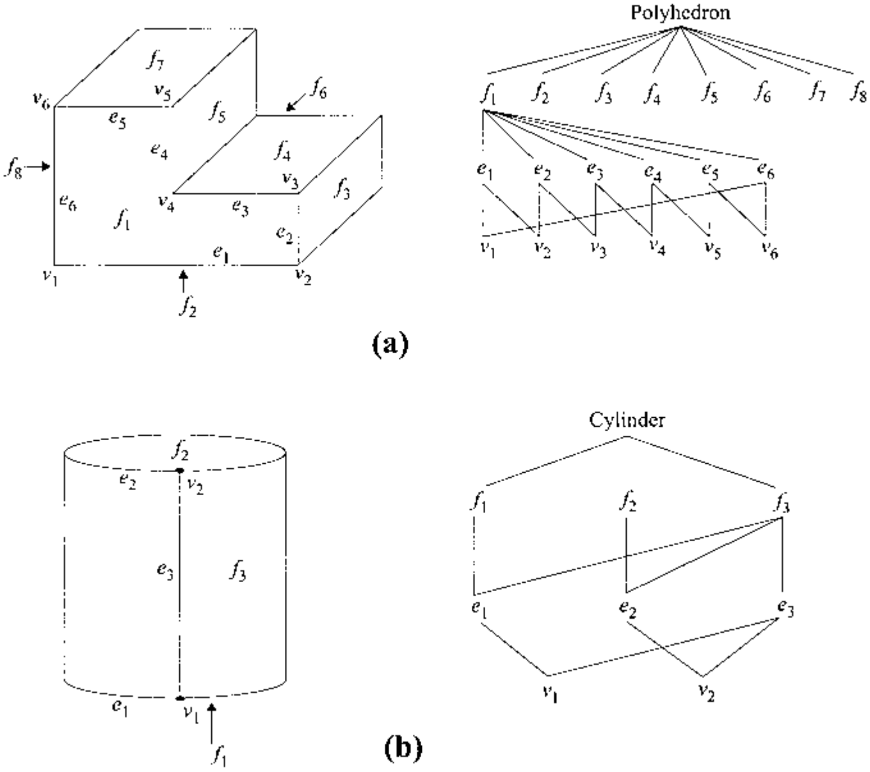


FIGURE 10 A polyhedron and a cylinder.

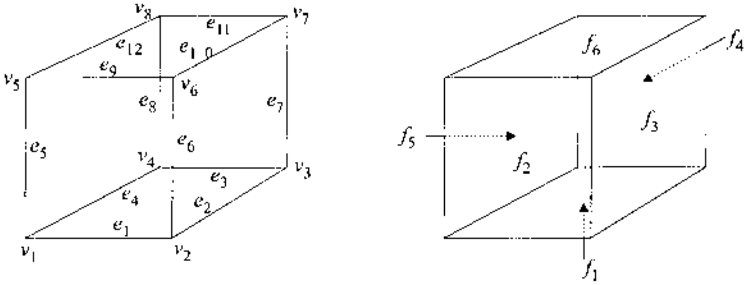


FIGURE 11 A polyhedron.

further by describing the adjacency of the edges through a directed search through the loops. The "winged-edge" data structure, first introduced by B. Baumgart, is commonly used for this purpose. It identifies a "first" edge for every face and a (loop) transverse direction for every edge, thus identifying the "next" edge on the loop. For example, let us consider the polyhedron in Fig. 11 and its partial winged-edge structure in Table 1, where cw is clockwise and ccw is counter-clockwise, ncw is next clockwise edge, pcw is previous clockwise edge, etc.

In Fig. 11, for Face 2, we start with the edge e_9, identify the face f_2, as a clockwise adjacency, and corresponding next clockwise(ncw) edge as e_6 (Table 1). Following around the loop, we next identify e_1 and e_5 and eventually close the loop at the vertex v_5 by noting e_9 again.

The B-Rep model of a solid object can also be represented via vertex, edge, face, or even loop information using graph theory, where the nodes identify the individual elements and the branches define connectivity. (Some graphs are called "directed" graphs, since they identify adjacency direction.)

TABLE 1 Partial Winged-Edge Data Structure

Face	First edge	Edge	fcw	ncw	fccw	nccw
f_2	e_9	e_9	f_2	e_6	f_6	e_{12}
.	.	e_6	f_3	e_{10}	f_2	e_1
.	.	e_1	f_1	e_2	f_2	e_5
.	.	e_5	f_2	e_9	f_5	e_4
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.

Information contained in a graph can be represented in a matrix form in order for algorithmic manipulation by CAD systems. Such an adjacency matrix is given here for the polyhedron's surfaces shown in Fig. 11, where 1 indicates adjacency:

Face	1	2	3	4	5	6
1	0	1	1	1	1	0
2	1	0	1	0	1	1
3	1	1	0	1	0	1
4	1	0	1	0	1	1
5	1	1	0	1	0	1
6	0	1	1	1	1	0

Adjacency matrices (and graphs) are commonly used in feature-based design for feature identification (extraction), as will be discussed in Section 4.4.

4.3.4 Model Conversions

Both solid-modeling methods discussed above, and others that were not detailed herein, have their virtues, which commercial CAD software designers take advantage of. CSG models are quite concise and have the advantage of being (relatively) easily convertible to B-Rep models, which in turn are useful for graphical outputs.

Solid modelers that allow user input, and subsequent data storage, in both CSG and B-Rep structures, are referred to as "hybrid modelers." Users of such a commercial CAD system, through a proprietary GUI, could model a part either through the CSG or the B-Rep modelers. In both cases, the part model is, subsequently, stored as a B-Rep data structure. However, segments of the solid model that are built through CSG will also have a CSG history tree for future CSG-based modifications, but not vice versa. Parametric modifications can be carried on both CSG and B-Rep built models, but parts of the model that were originally built via B-Rep cannot be modified using a CSG modellers (Fig. 12).

Both I-DEAS and Pro-Engineer CAD software packages allow designers to generate solid models using the CSG and B-Rep principles: first, a part's topological information can be "sketched" in two-dimensional space and subsequently "extruded" along three-dimensional curves to create simple primitives ("features"); several "features" can then be combined to create "parent–child" relationships. Both softwares keep track of the history

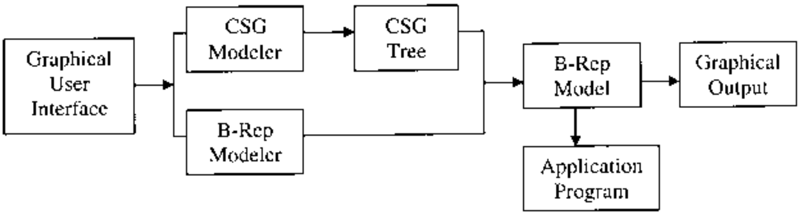


FIGURE 12 Architecture of a hybrid solid modeler.

of the Boolean operations and allow users to go back in history to modify the geometries of individual primitives.

4.4 FEATURE-BASED DESIGN

From a manufacturing engineering point of view, features can be seen as specific geometric shapes on a part that can be associated with certain fabrication processes. Thus it has been long advocated that if these features were highlighted during the modeling phase of a product's design process, in the subsequent production-planning phases, engineers could take advantage of this information in accessing historical data regarding the production of these features. Naturally, the engineers would have to be provided with material, tolerancing, and other pertinent data to complement the identified geometric (feature) information in reaching production decisions. In this chapter, as a continuation of the topic of geometric modeling, our emphasis will be on geometric (form) features and their utilization during the product-design process. That is, we will discuss the topic commonly referred to as design by features.

Features have been commonly classified by J. J. Shah and others as form, material, precision, and technological features. Form features identify geometric elements on the main body of a part (holes, slots, ribs, bosses, etc.) (Fig. 13). Material features capture material-composition and heat-treatment information. Precision features refer to tolerancing data. Technological features represent information related to the product's expected performance parameters.

The objective of design by features, as mentioned above, is twofold: (1) To increase the efficiency of the designer during the geometric-modeling phase, and (2) to provide a bridge (mapping) to engineering-analysis and process-planning phases of product development. The former can be achieved by providing designers with a library of features (not "primitives," as previously discussed in the context of CSG), from which they can pick

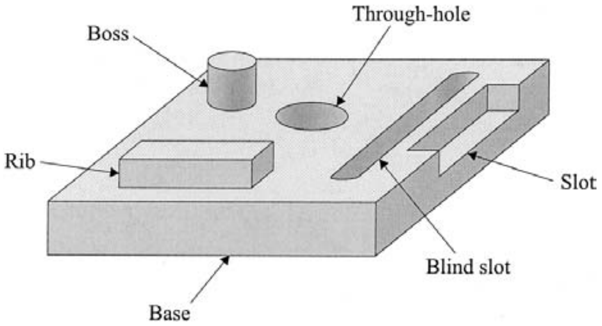


FIGURE 13 Common form features.

and place on the main configuration (body) of a part, or allowing them to extract (identical or similar) features from previous solid models of parts without an extensive feature library.

CAD research on design by features can be traced back to the work of several individuals at the University of Cambridge (A. R. Grayer, K. Kyprianou, and others) in the mid-1970s. Since then, there have been many noteworthy works that advanced the state of the art in feature-based design theory (by J. Shah, M. R. Henderson, R. Gadh, M. Mäntylä, and many others). Current numerical CAD packages have benefited from these works and do offer (limited) design-by-features capabilities. However, research in the field is still going on, the emphasis being on automatic recognition and identification of features from parts' solid models (primarily B-Rep models).

4.4.1 Design by Features

In feature-based design, parts' solid models are configured through a sequence of form-feature attachments (subtractions and additions) to the primary (base stock) representations of the parts, which can be as simple as a rectangular box (Fig. 14). These features could be chosen from a library of predefined (and sometimes application dependent, for example casting/molding/etc.) features or could be extracted from the solid models of earlier designs. The latter issue will be discussed in greater detail in subsection 4.4.2.

As is the case with many commercial CAD systems, form features can be individually modeled by the user explicitly using a B-Rep modeler (yielding unambiguous topological relationship information) or implicitly using a CSG modeler (yielding a tree representation of corresponding primitives and Boolean operators). Any attempt to generate a universal set of features must cope with the problem of database management—

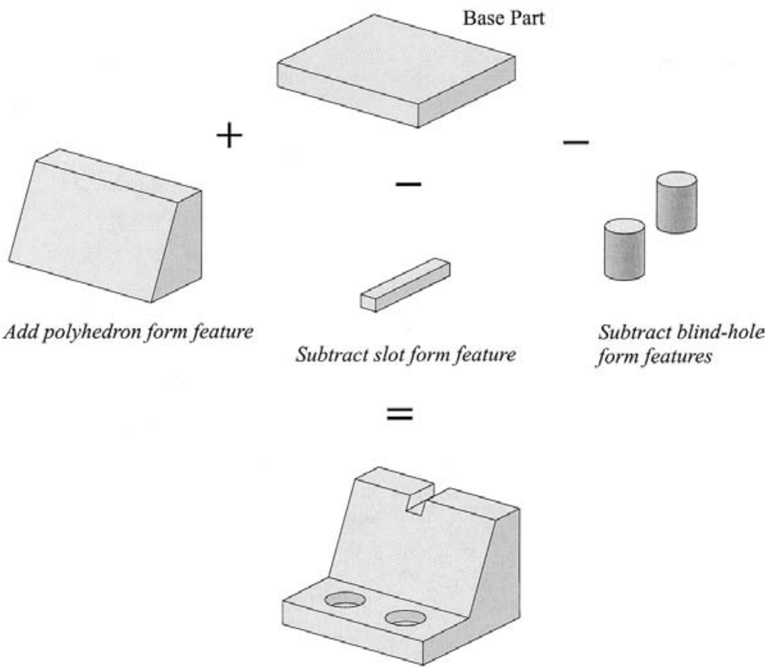


FIGURE 14 Design by features example.

storage and retrieval of form features, whose numbers may become unmanageable. A potential tool in dealing with such a difficulty would be the utilization of a logical classification and coding system for the form-feature geometries, such as a GT-based system (Chap. 3). In working with such a feature-based design system, the user would require the CAD system to search through the database of previous designs, identify similar features, and extract them for use in the modeling of the part at hand.

4.4.2 Feature Recognition

Automatic feature recognition normally refers to the examination of parts' solid models for the identification of features that have been predefined. The primary objective is not feature extraction per se but identification of the existence of a specific feature for the extraction of, for example, pertinent manufacturing information,. There have been numerous techniques proposed in the literature for the subsequent phase of feature extraction and use in solid modeling. However, one may question the need for the extraction of the geometric information of an already known entity. Thus recently there have been research efforts in developing extraction methods that would examine parts' solid models for the existence of geometric features, which have not been predefined, and extract them. Such features could then be classified and coded for possible future use in a GT-based CAD system. These features would continue to be part of the overall solid model of the part but be extractable in the future based on a user-initiated search for the most similar feature in the database via a GT code.

The two most important feature-recognition categories to date are (1) graph matching and (2) volume decomposition. Graph matching, normally, refers to topological matching in terms of the connectivity of faces that define form features within a B-Rep solid model. S. Joshi and T. C. Chang's work (based on the original work of Kyprianou) is most noteworthy in this subfield. Their work advocates the use of an attributed adjacency graph (AAG) for the definition of form features, where nodes represent faces and arcs represent adjacency with an assigned value of zero for convex and one for concave relationship. Using such a method a graph representation of a part's solid model is partitioned with respect to its features (Fig. 15). One must not, however, underestimate the computational effort required in trying to identify and match subgraphs for the recognition of form features.

The volume decomposition approach to feature extraction was developed by T. C. Woo in the early 1980s and later modified by numerous researchers, most notably by Y. S. Kim. In this approach, features are defined as volumes and decomposed from the part's solid model by subtraction (of primitives), yielding a tree structure, the nodes of which indicate Boolean operators (as in CSG), and the extracted features are the lowest leaves of the tree. Predefined features are then compared and matched to these volumes (features).

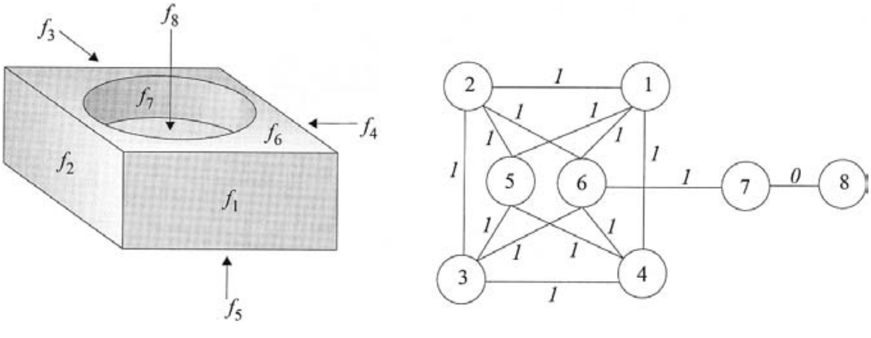


FIGURE 15 Face connectivity.

4.5 PRODUCT-DATA EXCHANGE

Despite intensive standardization efforts in the computing industry in the past two decades, almost all CAD hardware and software packages in commercial use today employ proprietary data-manipulation and data-storage formats. Thus, although large manufacturing companies can enforce the utilization of identical CAD systems within their enterprises, even they would face an uphill battle in data transfer between these systems, and other engineering analysis (CAE) manufacturing planning (CAM) software systems they employ. The problem gets quite complex due to variety of CAD/CAE/CAM systems used by the many companies that comprise the supply chain of different products.

4.5.1 IGES

The problem of exchanging design information between dissimilar systems has been under investigation since the late 1970s, even before the widespread commercial use of the Internet and the Web. The initial efforts concentrated on the exchange of graphics information between different CAD systems, which yielded the first version of IGES (Initial Graphics Exchange Specification), which was made available in 1980. IGES 1.0 was designed as a neutral format primarily for the exchange of mechanical part drawings (graphics).

This version of the IGES specification was based on Boeing's Database Standard Format (DBSF), which was influenced by the CAD systems then in use at Boeing, Computervision's CADDS 3 and Gerber IDS. Both relied on simpler geometric elements and their drafting packages included only basic text and dimensioning abilities. This version of IGES neither relied on a formal definition language nor did it require conformance to the specification.

IGES 2.0 followed the initial version and became available in 1983, with subsequent releases of IGES 3.0 in 1986, IGES 4.0 in 1988, and IGES 5.0 in 1990. These versions considerably extended the scope of the first version to include solid geometry (CSG and B-Rep) and finite-element modeling exchange capability. When additions to the specification list were considered, however, any entity had to exist in at least three major CAD systems before it would be considered for inclusion in IGES. IGES was targeted for the lowest common denominator, excluding many innovative unique features. The IGES standard, currently in its sixth revision, has been expanded to include most concepts used in major CAD systems. Although IGES has been intended as a neutral format, not tied to any particular CAD system, it still represents the entities of some CAD systems better than it does others'.

Exchanging data using IGES requires two modules, one on each CAD system: an IGES preprocessor on the first CAD system that would read the data file to be translated and produce an external file formatted in accordance with the IGES specification, and an IGES postprocessor on the second CAD system that would read the transferred file and translate it to the recipient's data format.

Many commercially available IGES processors today only support IGES Version 3, a few support IGES Version 4, and only a very few support IGES Version 5 and above (Version 5.3 being the latest). Support is generally best for elementary geometric entities, not so good for more complex geometric entities like B-splines and even annotations and dimensions, and almost nonexistent for concepts like features and assemblies. Thus it is advised that companies that rely on IGES rigorously test the capabilities of their processors to discover what does not transfer well. One can then either stop using the entities that do not work, or modify the output IGES file (manually or automatically) to work better with the second CAD system.

Currently, the IGES Specification is overseen by the IGES/PDES Organization (IPO). The IPO has been officially recognized by the U.S.A.'s National Institute for Standards and Technology (NIST) as the official organization responsible for the content of the IGES Specification. The IPO is also responsible for the U.S.A.'s input to the content of the PDES (Product Data Exchange using STEP) standard.

4.5.2 STEP

In mid 1980s, in response to foreseen serious deficiencies with IGES, the European Commission and U.S.A.'s NIST encouraged and funded projects for the development of a more comprehensive data-exchange specification. The primary result was the birth of PDES (Product-model Data Exchange Standard). Thus now the acronym PDES commonly refers to Product Data Exchange using STEP (STandard for the Exchange of Product model data). STEP, a derivative of PDES, was first proposed in 1984, resubmitted for approval both in 1988 in Tokyo and in 1989 in Frankfurt, but only achieved international standard status in 1994.

STEP - ISO 10303, provides a neutral computer-interpretable representation of product data intended to be used throughout the life cycle of a product, independent of any particular CAD/CAM system. As indicated above, its evolution and development took place under the auspices of the International Organization for Standardization (ISO) Technical Committee 184, Subcommittee 4. However, from the very beginning, it has been agreed that STEP needed to be developed in parts and offered as a replacement to

IGES, incrementally, as its parts reached maturity. STEP is currently organized as a series of parts that fall into one of the following categories: description methods, integrated resources, application protocols (APs), abstract test suites, implementation methods, and conformance testing.

APs define the information needed for a particular application and how this information is to be exchanged. These protocols draw on information encapsulated within the integrated resource models. STEP uses a formal specification language, EXPRESS, to specify precisely and consistently the product information to be represented. Some STEP APs that have achieved International Standard (IS) status are these:

AP201 Explicit Drafting
AP203 Configuration Controlled 3D Designs of Mechanical Parts and Assemblies
AP207 Sheet Metal Die Planning and Design
AP209 Composite and Metallic Structural Analysis and Related Design
AP210 Electronic Assembly, Interconnection and Exchange
AP213 Numerical Control Process Plans for Machined Parts
AP214 Core Data for Automotive Mechanical Design Processes
AP219 Manage Dimensional Inspection of Solid Parts or Assemblies
AP220 Process Planning, Manufacturing, Assembly of Layered Electrical Products
AP223 Exchange of Design and Manufacturing Product Information for Cast Parts
AP224 Mechanical Product Definition for Process Planning Using Machining Features
AP233 Systems Engineering Data Representation
AP235 Materials Information for the Design and Verification of Products

(Note that only AP201 and AP203 were part of the initial release of STEP in 1994. AP202 did not achieve ISO status until 1996, and APs 207 and 224 were published in 1999.)

AP203: Configuration-Controlled 3D Designs of Mechanical Parts and Assemblies

AP203 encompasses the following:

Product definition data and configuration control data pertaining to the design phase.
Five types of shape representations of a part that include wireframe and surface without topology, wireframe geometry with topology,

manifold surfaces with topology, faceted boundary representation, and boundary representation. (It excludes the use of constructive solid geometry for the representation of objects.)
Identification of other specifications for design, process, surface finish, and materials.
Data that identify the supplier of either the product or the design.

AP203 allows users to exchange geometry, topology, and configuration management data of a part or the whole product assembly. Although the parametric and layer information are not included, the solid-to-solid translation capability eliminates most of the modifications currently required when using alternative translation methods, such as IGES. AP203, being implemented by most CAD vendors today, is by far the most widely used application protocol.

AP214: Core Data for Automotive Mechanical Design Processes

AP214 encompasses the following:

Process plan information to manage the relationships among parts and the tools used to manufacture them
Product definition data and configuration control data pertaining to the design phase
Identification of standard parts, which have been classified according to national or industrial standards, and of library parts
Data that identify the supplier of a product and any related contract information
Any of eight types of representation of the shape of a part or tool: 2D-wireframe representation, 3D wireframe representation, geometrically bounded surface representation, topologically bounded surface representation, faceted boundary representation, boundary representation, compound-shape representation, and constructive-solid-geometry representation
Representation of portions of the shape of a part or a tool by form features
The simulation data for the description of kinematic structures and configurations of discrete tasks
Surface conditions and tolerance data

Although AP214's primary focus is the automotive industry, it includes many manufacturing-engineering processes common to other industries (for example, the aerospace industry). The capability of AP214 can be seen as a superset of AP203: it further includes the capability to exchange CSG-model, color, and layer information.

The recently released AP224, *Mechanical product definition for process plans using machining features*, may provide the necessary environment for the integration of part design with the process planning and production scheduling systems of an enterprise through the use of feature-based design. Although AP224 is presently available commercially on the ProEngineer platform via a third-party supplier, most other STEP-related products are limited to several conformance classes of AP203 and AP214. However, it is important to remember that STEP presents a powerful and robust technology beyond that currently implemented. STEP is still evolving, and it is now at a point when a significant number of APs will be reaching international standard status in the first few years of 2000.

Although, as in other formats, STEP-based data exchange is achieved through pre- and postprocessors, there exists an important difference between STEP and other data-exchange standards (IGES, Autodesk's DXF, and others): the alternatives normally deal only with particular application areas or products. STEP, on the other hand, is intended to store all data in an integrated form for a product throughout its life cycle without regard to discipline or application area. Data integration ensures that the information describing product design, manufacturing, and life cycle support is defined only once, thus eliminating redundancy and associated problems caused by maintaining redundant information.

Some industrial users of STEP are listed here:

Lockheed–Martin and some of its suppliers have collaborated on the design of the F-16 and F-22 jet fighter aircraft, while using STEP for exchange of technical data.

Bristol Aerospace has used STEP in the design of aircraft structures to customer requirements by allowing the sharing of three-dimensional solid modeling data.

Boeing Airplane and Pratt and Whitney, Rolls–Royce and GE Aircraft Engines have used STEP to help verify the form and fit of the parts that integrate the engines and the aircraft in the 777 and 767-400 planes.

General Motors has extensively used STEP to transfer the designs of vehicle models between its various divisions as well as its first-tier suppliers (Delphi Automotive Systems, Delco Electronics, and others).

REVIEW QUESTIONS

1. What is the primary purpose of geometric modeling in the context of computer-aided engineering (CAE)?

2. What is the primary purpose of solid modeling in the context of geometric modeling?
3. Why should designers be aware of various curve-fitting or surface-fitting techniques? What is the difference between a least-squares fit and a spline fit? Choose two products that have "free" surfaces (e.g., car body, dental implant) and recommend a least-squares fit or a spline fit. Justify your answers.
4. Why would an engineer decide to use Bézier (curve or surface) fits versus other approximations?
5. Although there exists a number of solid modeling techniques, users of various computer-aided design (CAD) packages may not be even aware of the variety and model objects in intuitive ways as opposed to using formal techniques. Review your knowledge of an existing CAD package and discuss the ways the software allows you to model three-dimensional objects while comparing those to the following formal techniques: primitive instancing and sweeping, constructive solid geometry, and boundary representation.
6. Describe the possible different object design features. Define the process design by features.
7. Why is feature recognition an important capability that would allow the widespread use of design by features?
8. Data-exchange protocols/standards/specifications allow users of different commercial CAD/CAE packages to work in a more coherent manner on the concurrent design of complex products in the virtual domain. Compare the two most common data-exchange specifications, IGES and STEP, respectively.

DISCUSSION QUESTIONS

1. Computer-aided design (CAD) of engineering products has been practiced as long as there have been computers in existence (since the early 1950s). The term CAD, however, has often been misused as solely "the employment of commercial engineering modeling software." These packages, which have been in existence only since the late 1970s, when compared to earlier ones, provide users with powerful graphical user interfaces (GUI) for the modeling of parts/products and graphical display of engineering analysis results. In the above context, discuss the role of current CAD packages in the design (synthesis and analysis) of engineering products.
2. Geometric modeling is a design task that can be efficiently implemented using a commercial CAD package. Discuss the importance of geometric modeling for the synthesis and analysis stages, or even potentially for

virtual reality modeling cases, of design. Address issues such as surface modeling versus solid modeling.

3. Part designs can be classified and coded using a group-technology (GT) technique, primarily to allow access to (past) similar designs. Would several different GT-based classification and coding systems be needed in a company for different objectives? That is, one system for design, one system for manufacturing planning, and yet another for cost engineering?
4. The use of design features has long been considered as improving the overall synthesis and analysis stages of products owing to the potential of encapsulating additional nongeometric data, such as process plans, in the definition of such features. Discuss feature-based design, where the user, through some recognition/extraction process, can access and retrieve individual similar or identical features on earlier product designs and utilize them for the design of the product at hand. Furthermore, compare such a design approach to a primitives-based design, where the user generates or accesses a limited-size database of geometric primitives for the design of a new product.
5. The majority of commercial CAD packages store geometric and nongeometric data using proprietary techniques. Discuss the importance of standardization of the data management process for CAD packages, including the use of data exchange interfaces, in the new economic reality of "distributed design" within large and complex supply chains.
6. In the near future, although the majority of engineering products will be modeled in the virtual (computer) space, representing the starting point of the design and manufacturing process, some products will still be crafted manually by artisans and/or industrial designers. Discuss the computer-aided modeling and analysis of such products, whose features are not originally defined by exact mathematical relationships. Consider and use some specific product examples in your discussion.
7. Computers and other information management technologies have been commonly accepted as facilitators for the integration of various design activities. Define/discuss "integrated design" in the modern manufacturing enterprise and address the role of computers in this respect. Discuss the role of suppliers in such design activities.

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