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Using Geometric Constraints to Capture Design Intent

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Abstract. With the use of geometric constraints, parametric and variational solid modeling systems enable designers to incorporate relationships between geometric entities into the geometric model and thereby control potential changes in geometry. The objective of developing these constraints or relations is to capture the intent of the designer and restrict changes that may be made by other users of the model. This paper will describe methods and strategies for constraining geometric models and show how these models capture design intent.

Key Words: CAD, geometric modeling, parametric modeling, variational modeling, design intent

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1. Introduction

Computer Aided Design (CAD) systems have developed over the past 35 years from simple sketching tools such as Sketchpad (SUTHERLAND [7], 1963) to sophisticated design tools based on parametric and variational feature-based solid geometric modeling systems. Commercially available systems include PTC's Pro/Engineer, SDRC Ideas, MacDonald/Douglas Unigraphics, Solidworks, AutoDesk Designer, and several others. In addition to providing geometric models of the product, these systems have integrated analysis and manufacturing applications that are directly linked to the geometric models (CHASEN [2], 1996). The associative database can be used to record and store extensive product information, not just geometric specifications. Design histories that document design decisions and changes can also be stored with some of the more sophisticated systems (HANRATTY [3], 1995).

In a highly competitive, global market, manufacturers face increasing pressure to provide improved products and reduce the time and expense of product development. Thus, designers and engineers need to develop new strategies for product design. Previously, this author has discussed modeling strategies for the use of solid modeling systems ([1], 1995). Constraint-based systems require further modeling strategies to create the most useful CAD models.

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These strategies must take advantage of the capabilities of the design tools to capture design intent and modify or reuse the design. One method of incorporating design intent into the geometric model is through the use of geometric constraints and design equations. This paper discusses strategies for capturing design intent in the geometric model and provides a case study to illustrate the method.

2. Parametric and variational models

2.1. Parametric models

Parametric and variational solid models use a set of equations to determine the size and shape of the solid. The model is based on finding a compatible set of positions for each vertex within the solid. Parametric modelers use an iterative, sequential solution strategy with limited constraint options and special case solution search methods. Parametric systems can be used to model a wide variety of commonly designed parts. They are easy to use, have rapid response time for updating models, and do not allow unintentional geometric inversions or changes in topology. The sequential solution modeling and solution strategy automatically records design history. These systems cannot model parts that require the use of coupled design equations and constraints. The model must be fully constrained before a solution can be found (Schussel and Chung [6], 1996).

2.2. Variational models

Variational modelers are not limited to specific classes of constraints (as are parametric models) and solve the equation set simultaneously. Based on the design equations, a solution is found which satisfies all of the constraints and generates a valid solid object. Solution times are generally slower than parametric modelers, and solutions may result in undesired configurations of the geometry. However, these systems can model all conceivable geometries, including those with coupled constraints. Under-constrained models can be used, a feature which is very useful during the early stages of design [6]. Commercial software is typically classed as constraint-based modelers, and those packages listed in Section 1 include both parametric and variational systems. Some hybrid systems are also available, thus, the distinction between software packages is not clear cut. The designer should select a system which provides the required modeling capabilities for the types of parts to be modeled.

3. Constraints

3.1. Constraint modeling

Constraint-based systems allow the position and size of all geometric elements or entities to be specified using variables. This enables the designer to create a geometric model which is easily modified during the design process. In the case of a simple 2D parametric model, for example, a triangle is specified by the locations of three vertices, P_1 P_2 and P_3 (see Fig. 1).

Six equations are needed to fully specify the x- and y-coordinates of the three points (in 2D). Information in the database concerning connectivity and entity types associated with each point or vertex in the model is then used to generate the desired geometry (line segments for the triangle), but the basic geometry is fundamentally defined from the positions of a set of data points or vertices. In its simplest form, the equations for the triangle would consist

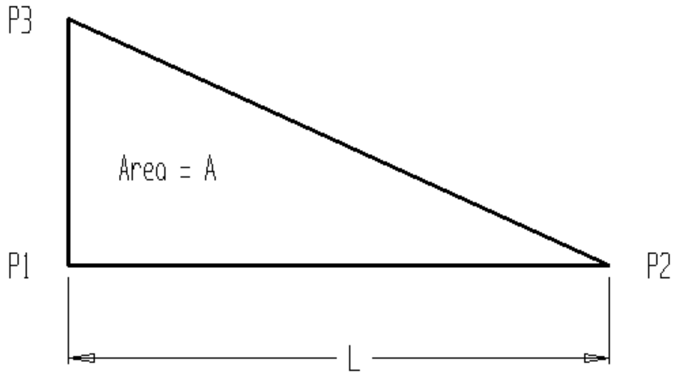

Figure 1: Triangle model used for constraint examples

of the assignment of values for each coordinate location (point $P_1:\ x_1 = 5,\ y_1 = 4$, etc.). In this case there are no constraints or relations between the entities and the model is fixed, with no variational or parametric capability. Using variables instead of the constants in the assignment equations would allow the model some variational capability. This leads to a highly flexible and very general model of the triangle, but it is a very awkward model to use for design purposes. Constraints are needed to control the shape and incorporate assumptions typically used in design (Light and Gossard [4], 1972).

3.2. Constraint types

Modeling constraints can be classified as four types: ground, dimensional, geometric, and algebraic (Mantyla and Shah [5], 1995).

3.2.1. Ground constraints

Ground constraints provide references between the part and the global coordinate system. Locations of specific points and horizontal and vertical constraints on line segments are typical examples of ground constraints.

3.2.2. Dimensional constraints

Dimensional constraints provide numerical values for basic geometric entities. For example, the length of one side of the triangle might be specified using an equation of the form:

$$\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} = L$$

where L is the dimension or design parameter for the length of the line segment P_1P_2. Parametric modeling systems allow users to vary these design dimensions. Dimensional constraints may be used to indicate the size of specific entities such as a line segment or radius of an arc, or they may be applied to any two points on the model to control the distance between those points.

3.2.3. Geometric constraints

A geometric constraint imposes relationships between geometric entities such as tangency, collinearity, parallelism, perpendicularity, coincidence of points, symmetry, etc. If two line segments, defined by points (x_1, y_1), (x_2, y_2) and (x_3, y_3), (x_4, y_4) are perpendicular, for example, an equation of the form:

$$\frac{y_2 - y_1}{x_2 - x_1} = -\frac{x_4 - x_3}{y_4 - y_3}$$

is required to impose the desired constraint.

3.2.4. Algebraic constraints

Algebraic constraints impose restrictions on design dimensions in the form of mathematical equations. The designer might wish to make one line segment length equal to twice the length of a second line segment, control the aspect ratio of a rectangle, or set a constant area for a profile section. Algebraic constraints may be equalities, inequalities or conditional statements. Inequalities may be used to limit the size of an entity or feature, either in absolute value or in comparison to another geometric entity. Logical expressions (IF–THEN or CASE statements) allow the designer to develop more complex relationships between the geometric parameters.

3.3. Development of constraint equations

All four types of constraints (ground, dimensional, geometric, and algebraic) can be used to capture design intent. Some constraints may be imposed automatically by the software based on assumptions such as horizontal and vertical placement of lines, etc. In general, CAD systems will allow the designer to specify dimensional values, specify geometric constraints between entities, and write algebraic expressions. Based on this input from the designer, the system generates the necessary constraint equations for the individual points.

For example, consider the triangle with vertices at P_1, P_2 and P_3 shown in Fig. 1. The side P_1P_2 has a length L and the area is A. The fully constrained triangle requires six equations. With assumptions that the legs of the right triangle are horizontal and vertical, and given a reference position for P_1 as stated above, the six equations are:

$$\begin{gathered} x_1 = 5\,, \qquad\qquad y_1 = 4\,, \\ y_2 = y_1\,, \qquad\qquad x_3 = x_1\,, \\ (x_2 - x_1)^2 + (y_2 - y_1)^2 = L^2, \\ (x_1y_2 + x_2y_3 + x_3y_1 - y_1x_2 - y_2x_3 - y_3x_1) = 2A\,. \end{gathered}$$

The first four equations represent ground constraints, the fifth is a dimensional constraint, and the last equation is an algebraic constraint. Note that the general equations for length and area could be simplified if the assumptions of horizontal and vertical constraints are known a priori, however, the system may not have symbolic manipulation capabilities for algebraic simplification, therefore, the system will usually solve the more general set of equations.

4. Design strategies

Unlike conventional CAD systems, variational or parametric modeling systems allow the designer to alter design dimensions without making a new geometric model. In general, the designer wishes to change the size of various features but in general, the topology remains constant. In addition, the designer may wish to maintain certain relationships between design variables. However, other users of the model may inadvertently alter the desired shape, size, topology or other features of the geometry. Furthermore, automated design software may be used to analyze the model and explore the effects of changes in the design variables (dimensions). Without careful development by the designer, the design intent can be lost. Thus, the designer must incorporate as many constraints within the model as needed to ensure that his/her design intent is retained when the model is modified. The geometric model should allow maximum flexibility to permit design changes yet be sufficiently robust to prohibit undesirable changes which alter topology or violate design intent. Design intent may include constraints that control functional characteristics of the part or feature, manufacturing considerations, strength, relationships between features, etc.

4.1. Example #1: Valve plate

Fig. 2 shows a conventional 2D drawing of the valve plate for a small steam engine (Verburg [8], 1986). This simple rectangular plate contains sufficient geometry to demonstrate the principles of capturing design intent through the use of constraint equations. Features of the plate include four holes in the corners used to bolt the valve plate to the steam chest and a rectangular grid of holes in the center of the plate to allow passage of steam from the steam chest into the engine cylinder.

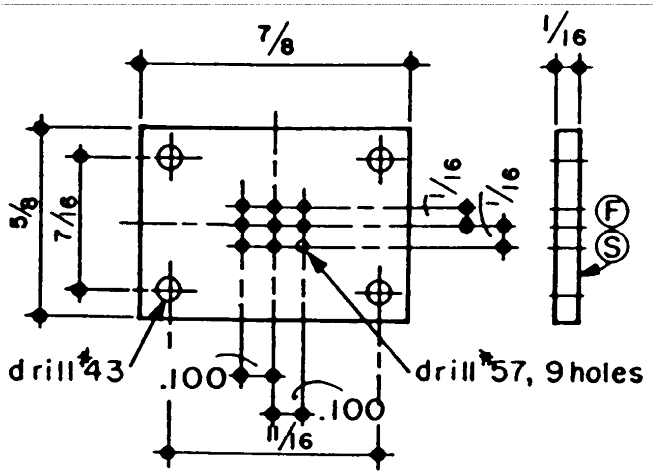

Figure 2: Conventional drawing of valve plate (Verburg [8])

Fig. 3 shows the same part with independent parameter values assigned to the dimensions according to one possible modeling strategy. Dimensions not shown are dependent upon those given through the constraint equations. Some CAD systems include "smart" sketching tools that will automatically impose certain constraints. Others may result from the construction methods used by the designer (mirror copy, patterning methods, etc.). However, the designer must be aware of the implications and the constraints that are imposed as a result of using such construction methods.

The part is modeled as a solid rectangular extrusion. One corner hole feature is added, then the remaining three holes are added using translation copy which forces the holes to be of equal size. One steam hole is added, from which a rectangular array of identical holes is generated. Note that there is no unique modeling or dimensioning scheme for the part. A variety of modeling strategies exist that will result in different combinations of parameters or dimension variables. The designer must select a modeling strategy and dimensioning scheme that will facilitate the development of the parametric model and constraints that can be used to capture the design intent.

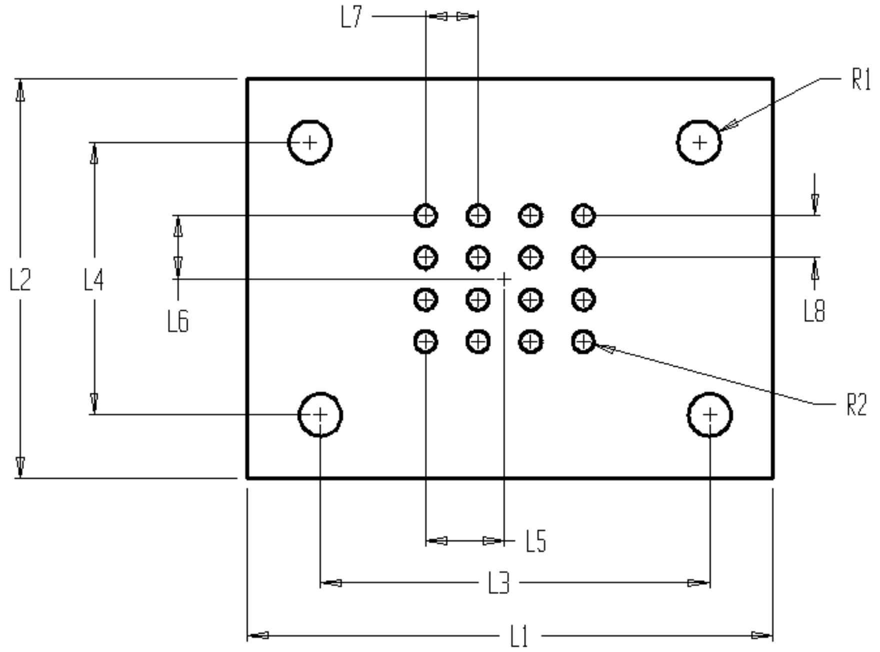

Figure 3: Parametric model of valve plate

For manufacturing and assembly purposes, it is desirable to have all of the corner bolt holes of equal diameter (to be drilled with a single tool and assembled with uniform bolt size). By convention, standard drafting practice provides a note for the drill size on only one of the corner holes and all others are assumed to be of the same diameter (see Fig. 2). The machinist interprets the drawing accordingly. In the geometric modeler, all holes are individually dimensioned unless constraints are imposed. In this case, the constraint is imposed by the use of the copy command.

Likewise, symmetry is shown on the drawing with centerlines across the part. In this example, symmetrical placement of the corner holes is imposed by an algebraic equation generated by the designer. Additional dimensions (not shown) are needed between the left and bottom edges of the plate and the center of the first hole generated (lower left). If these dimensions are labeled L_9 and L_{10}, respectively, the necessary equations are:

$$L_9 = \frac{L_1 - L_3}{2}\,, \qquad L_{10} = \frac{L_2 - L_4}{2}\,.$$

Alternatively, the designer could have chosen a mirror copy command about a center plane in order to generate the desired constraints. This modeling strategy does not result in the generation of a dimension for the distance between the holes, a critical functional dimension for the part. This demonstrates how the designer must select appropriate modeling strategies and apply the necessary equality constraints to the model to ensure that downstream users of the model do not violate the design intent. This also facilitates later changes by linking all the holes to a set of dimensional parameters which are related to the functional requirements of the part and can be easily changed. Furthermore, mating parts in the assembly can also be constrained to this set of dimensions.

The size and placement of the steam holes can also be controlled through the use of design equations. Let us assume that the hole pattern is specified as a rectangular array of identical holes. Variables can be assigned to designate the number of holes in the vertical and horizontal directions (m, n). The designer can then write an equation which imposes a constant total hole area, regardless of the number of holes in the plate in the form:

$$A = \pi m n R_2^2 .$$

If m or n is changed, the diameter of the holes will change automatically.

Equations must also be written or constraints applied to maintain valid topology of the part. For example, the designer needs to limit the hole size such that there is adequate material between the hole and the edge of the plate. With a minimum wall thickness of t, these equations would be in the form of inequalities as follows:

$$R_1 \leq \frac{(L_2 - L_4)}{2} - t\,, \qquad R_1 \leq \frac{(L_1 - L_3)}{2} - t\,.$$

Additional equations could be written to prohibit overlapping of the steam holes with the bolt holes., mutual overlapping of the individual steam holes or bolt holes, etc.

5. Conclusion

Parametric or variational modeling systems have been developed to enable the designer to *"capture design intent"* in the geometric model of a part or assembly. This paper presented a case study which shows how constraints may be applied to the geometric model to create a flexible model while eliminating or reducing the possibility of undesirable changes to the geometry or topology of the model.

References

[1] H.K. Ault: *Modeling Strategies for Parametric Design.* Proc. 7th ICECGDG, Cracow, Poland, 390–394 (1996).

[2] S.H. Chasen: *A Little History of C4.* In C. Machover (ed.): The CAD/CAM Handbook, McGraw-Hill, 1996, pp. 1–9 .

[3] P.J. Hanratty: *Parametric/Relational Solid Modeling.* In D. LaCourse (ed.): Handbook of Solid Modeling, McGraw-Hill, 1995, Chapter 8.

[4] R. Light, D. Gossard: *Modification of Geometric Models Through Variational Geometry.* CAD **14**, no. 4, 209–214 (1982).

[5] M. Mantyla, J. Shah: *Parametric and Feature Based CAD/CAM: Concepts, Techniques and Applications.* John Wiley & Sons 1995.

[6] M.D. Schussel, J.C.H. Chung: *Constraint-Based Design Technologies.* In C. Machover (ed.): The CAD/CAM Handbook, McGraw-Hill, New York 1996, pp. 181–200.

[7] I. Sutherland: *Sketchpad, A Man-Machine Graphical Communication System.* PhD thesis, MIT 1963.

[8] E. Verburg: *Grasshopper Engine.* ModelTec Magazine, July 1986, 7–13 (1986).

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