A CAD/CAM Package for Free-surfaced Mould Cavities

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Abstract
This paper describes a microcomputer-based CAD/CAM package for the design and manufacture of mould cavities for producing products with simple free surfaces. A product surface may be described by specifying control points on its cross sections, through which spline curves are fitted along both traverse and longitudinal axes. The number of curves fitted depends on the required accuracy. The digitizer captures the control points of some cross sections of the pattern. The package reads these control points and fits a detailed surface of the pattern. The designed surface can be converted to obtain the shape of a mould cavity by manipulating it with geometric operations such as scaling, left-right inversion and male-female inversion. This package can also be interfaced with a 3-D digitizer to copy a given pattern. Triangular facets representing a wire-frame model of the surface can be generated for further analysis, such as shading and calculation of geometrical data of the surface. Cutter paths and hence the control codes for both rough and finish machining the mould cavity on an NC machine can be generated. A simple and easy-to-use module has been incorporated to enable the system to plan the cutter paths for efficient machining according to the specified cutter dimensions and allowable tolerance. An efficient and easy-to-use cutter path simulation module has been incorporated in this package.

Introduction
Products with simple free surfaces are quite common. Examples include plastic bottles for packaging liquid consumable, such as shampoo and detergent for general use. These products are commonly manufactured by blow moulding or injection moulding. The shape of these products has become more irregular as market competition demands a higher degree of aesthetics in packaging. The demand for aesthetical shapes, coupled with a general tendency to shorten the production lead time, has presented some problems to many local mould and die makers. Traditionally, mould cavities are machined by copying from a pattern, which is normally hand-made by a skilled craftsman. General CAD/CAM systems based on surface modelling techniques have been available for the design of products or dies with free surfaces[1]. However, specific functionality required to facilitate the surface design for mould cavities may not be available in these CAD/CAM systems. Furthermore, the machining functionality of these systems may not be as strong and easy-to-use as desired. In general, these systems cannot generate cutter paths for direct rough machining. They also cannot automatically plan the cutter paths to achieve a specified machining accuracy. The user could only guess the possible machining accuracy by specifying the number of cutter paths to be generated. Hence they may not be particularly suitable or economical for the design and manufacture of mould cavities. This paper presents a CAD/CAM package with specific utilities developed to help the design and manufacture of mould cavities for simple free surfaces. It is an enhanced version of a CAD/CAM package for bottles developed in the department. The package is based on the widely proliferated IBM PC compatible micro-computers. It is aimed to provide a simple and useful tool for the local mould and die manufacturers.

The CAD/CAM Package
The CAD/CAM package currently consists of the following major modules:

(1) Design of the surface of mould cavities.
(2) Interface with a 3-D digitizer for pattern duplication.
(3) Generation of data for geometrical analysis of the surface.
(4) Simulation of cutter paths for rough machining the surface or mould cavity.
(5) Simulation of cutter paths for finish machining of the surface or mould cavity.

Design of a Free Surface

Surface Contours

A free surface can be constructed from the contours of its cross sections. The cross sections are defined by the coordinates of some control points on traverse (x-y) planes perpendicular to the longitudinal (z) axis of the surface, as shown in Fig. 1. If the cross section is symmetrical about the longitudinal axis, only a half of the control points is needed and a mirror image of these control points is taken to complete the definition of the cross section. The package creates contours which describe the surface along both traverse and longitudinal axes by fitting spline curves[2] to the control points. Fig. 2 shows an example of the contours of a simple surface of a bottle. Having described the cross sections by specifying control points, the package automatically inserts intermediate contours between each pair of the cross sections to give a finer representation of the surface. The number of intermediate contours is adjusted according to the degree of accuracy required. A mesh patch consisting of triangular facets is then generated to form a wire-frame model of the surface. The wire-frame model can be further processed to generate a shaded surface to give a more realistic visualization of the designed surface. Geometrical data of the surface, such as volume and area, can also be calculated accordingly for analytical purposes, such as heat flow etc..

Shape Control along Longitudinal Axis

The traverse cross sections are generally taken at critical locations along the longitudinal axis so that the surface can be well described with a minimum number of cross sections. Better control of the shape can be achieved by increasing the number of cross sections. To fine tune the local smoothness of the surface, the control points of a particular cross section can be slightly shifted about. It is also possible to change the end-point conditions of the spline curves to obtain the required local smoothness. Furthermore, the contour curves can be forced to pass through the control points or made tangent to the line segments joining the control points.

The traverse cross sections are assumed to be perpendicular to the longitudinal axis of the surface. This assumption facilitates the design of the surface because the longitudinal axis of a surface is generally straight. However, it is possible to describe a 3-D spline curve for the longitudinal axis. This allows surfaces with relatively complicated shape along the longitudinal axis to be designed easily. Fig. 3 shows a surface with a straight longitudinal axis and one with a curved longitudinal axis.

Geometrical Accuracy

The geometrical accuracy of a modelled surface depends on the number of intermediate sections, which is affected by the specified maximum allowable chordal error. As shown in Fig. 4, the chordal error, e, is controlled by the number of intermediate contours along both traverse and longitudinal axes. The number of intermediate contours required to achieve a specified degree of geometrical accuracy is calculated according to the following method:

(1) The chordal error, e, of a curve segment and the line representing the plane of a facet is calculated. If e is greater than the specified precision, one intermediate control point is inserted.
(2) Repeat step (1) until all chordal errors are within the specified precision.
(3) Fit spline curves to the intermediate control points inserted above.
(4) Generate facets to form a wire-frame model of the surface, if necessary.

Shape Manipulation

Three types of operations are available for the manipulation of the surface or its cavities, namely *scaling, male-female inversion* and *left-right inversion.* The *scaling* operation is used to enlarge or reduce the size of the surface either independently or uniformly along the x, y and z axes. This operation allows a family of parts of different sizes to designed easily. The *left-right inversion* allows a surface of the mirror image of an existing surface to be obtained. This is useful for modelling cavities for blow moulding. The *male-female inversion* is used to obtain a convex surface from an existing concave one, or vice versa. The cross sections of the existing surface are firstly turned up-side down, and then left-right inverted. This operation is very useful for modelling cavities for injection moulding.

Generation of Surface Mesh Patch

If the surface designed is satisfactory, a mesh patch is generated by joining up each of the grids formed by the intersections of the traverse and longitudinal contours with two triangular facets. A wire-frame mode of the surface is formed by arranging these facets in a suitable format which is easily accessible by other modules or packages. The wire-frame model can be further analyzed for shading of the surface, calculation of heat transfer, simulation of plastic flow pattern, and calculation of geometrical properties, such as surface area and volume.

Interface with a 3-D digitizer for pattern duplication

The coordinates of control points for surface design are normally specified with a mouse or the keyboard. However, if a pattern of a product is available, its surface can be copied by measuring the control points of its cross sections with a 3-D digitizer or a coordinates measuring machine. The package reads these control points as input and generate a surface in the same way as it is designed. Hence the total number of points needed for duplicating a surface may be drastically reduced as compared with direct digitizing process. This is considered particularly useful for enhancing the efficiency of a 3-D digitizer.

Machining of the Surface

A *rough cut* module and a *finish cut* module have been implemented for generating cutter paths for machining the surface or its cavities. The user specifies the cutter dimensions, maximum allowable depth of cut and the required degree of accuracy. The cutter paths will then be generated according to these specifications.

Rough Cut

The rough cut module simulates the cutting process for bulk removal of the excess material from a rectangular block within which the surface or cavity is contained. This module scans a traverse section of the surface and feeds the cutter to remove the material until the cutter touches the surface. The cutter is then lifted and moved horizontally to avoid the crest of the section. This rough cutting process is repeated for all traverse sections by feeding the cutter layer by layer as specified by the allowable depth of cut until the parting plane is reached. This module allows a rough profile of the surface to be machined easily. Fig. 5 shows part of the simulated cutter paths for rough machining a surface.

Finish Cut

To obtain a good machined surface texture, the machining asperities, or cusps, must be controlled to an acceptable level. If the maximum allowable cusp height h as shown in Fig. 6 is specified, the centre distance s between two paths of a spherical cutter with a radius r can be calculated using the equation $s = 2\sqrt{h(2r-h)}$. The following algorithm has been implemented for automatic control of cutter paths for machining the surface to achieve the specified accuracy:

(1) Calculate the maximum possible centre distance, s, between two neighbouring cutter paths;
(2) Calculate the length of each longitudinal curve segment between each pair of adjacent layers, as shown in Fig. 7;
(3) Selected the maximum length, L, of the curve segments calculated in step (2);
(4) Assuming that s is small so that the curve segment in question approximates a straight line, insert [*INTEGER*(L/s) + 1] intermediate sections between the adjacent layers;
(5) If the distance between any pair of sections is less than s, insert one more section;
(6) Repeat steps (2) to (5) for another pair of adjacent layers until enough sections have been added to the whole model;
(7) Repeat steps (2) to (6) for traverse layers;
(8) Generate triangular facets;

(9) Generate cutter paths that run across the facets smoothly while maintaining the cutter tangent to the normal vector through the centroid of the facets[3,4] until the parting plane is reached;

(10) Generate the cutter paths for machining the parting plane with a flat-ended cutter, if necessary.

This algorithm has been found to be relatively efficient in that the simulation of machining a surface of general size and accuracy can be completed within a period of about 2 minutes. Fig. 8 shows a photograph of a bottle surface being machined on a CNC machine.

NC Post-processor

This module processes the data files containing the cutter paths for rough cut and finish cut. It generates NC part programs suitable for machining the surface or its mould cavity on a CNC milling machine with a FUNAC 6M controller. The NC part programs can be downloaded to the controller for DNC machining of the surface.

Conclusions

It can be concluded that a CAD/CAM package, based on an IBM compatible micro-computer, has been developed for the design and manufacture of mould cavities for production of parts with simple free surfaces.

Graphical menus and functional utilities have been developed to facilitate the description of a surface and its subsequent manipulation to obtain the mould cavities.

Modules for cutter path simulation have been developed for both rough machining and finish machining. These modules are capable of generating cutter paths for machining the surface with the required accuracy efficiently.

Further Development

To enhance the practicability of this CAD/CAM package, the following modules are considered worthy of further development.

(1) *Shading Module*
A module is being developed to process the wire-frame model for shading the surface. This provides a more realistic representation of the designed surface before machining is committed.

(2) *Windows Platform*
The package is currently a DOS version. It is now being ported to run on Windows platform to make use of the graphical utilities for better user interface.

(3) *Analysis Module*
A module using techniques such as the finite-element will be developed for the analysis or simulation of heat transfer and the plastic flow pattern in the mould cavity.

(4) *Generic NC Post-processor*
A generic NC post-processor will be developed to translate the cutter paths into NC part programs suitable for NC/CNC milling machines with control systems commonly used in the local industry.

References

[1] J.S. Gunasekera, *"CAD/CAM of Dies"*, Ellis Horwood, 1989.
[2] Carl de Boor, *"A Practical Guide to Splines"*, Springer-Verlag, 1978.
[3] J.P. Ducan, *"Sculptured Surfaces in Polyhedral Machining"*, McGraw-Hill, 1981.
[4] J.P. Ducan, *"Introduction to Polyhedral NC Concept"*, Lectures in Hong Kong 1989.

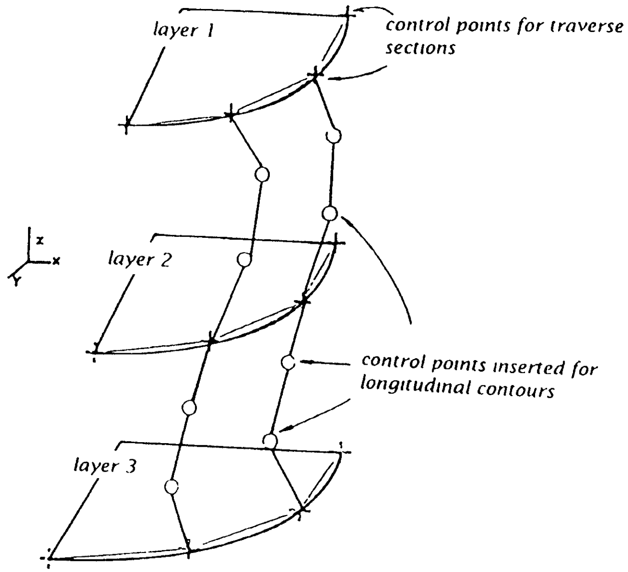

Fig. 1 Control points for cross sections

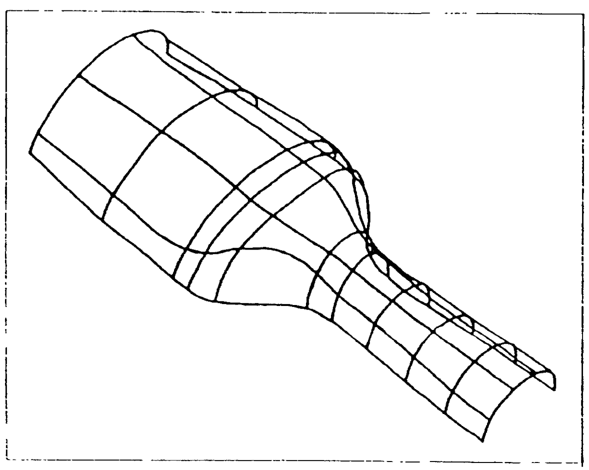

Fig. 2 An example of a bottle surface

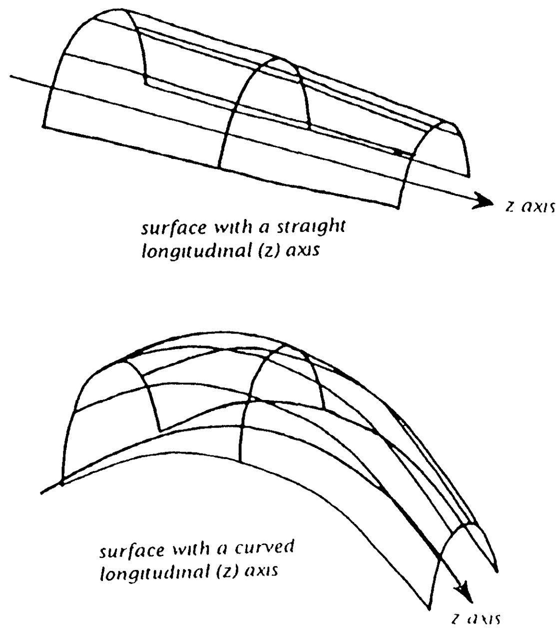

Fig 3. Surfaces with a straight z-axis and a curved z-axis

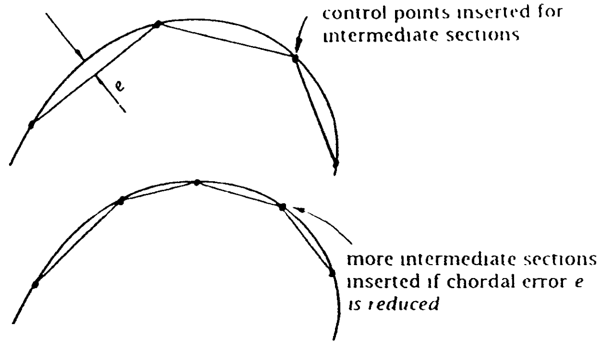

Fig. 4 Chordal error

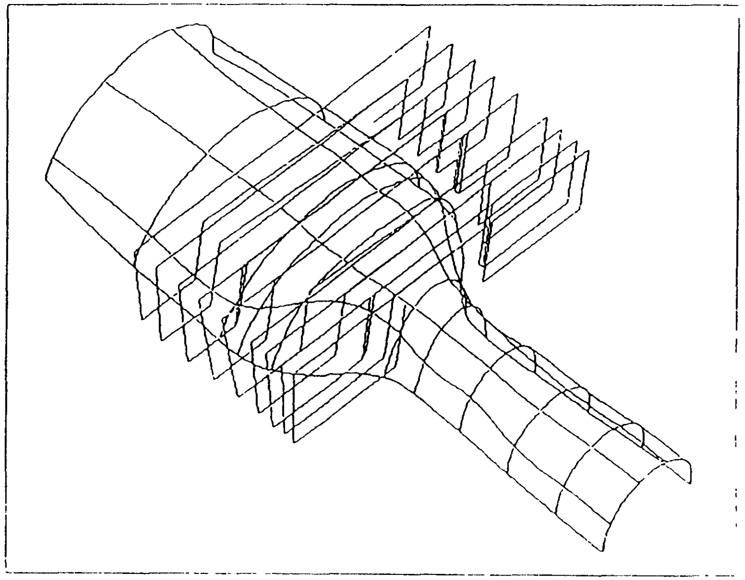

Fig. 5 Part of the simulated cutter paths for rough machining

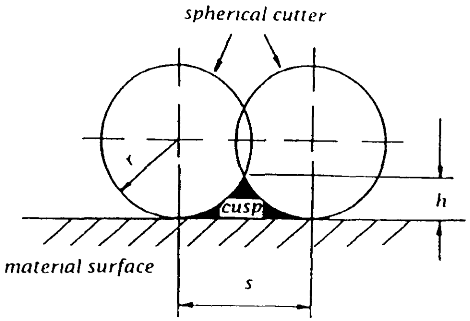

Fig. 6 Calculation of cutter centre distance

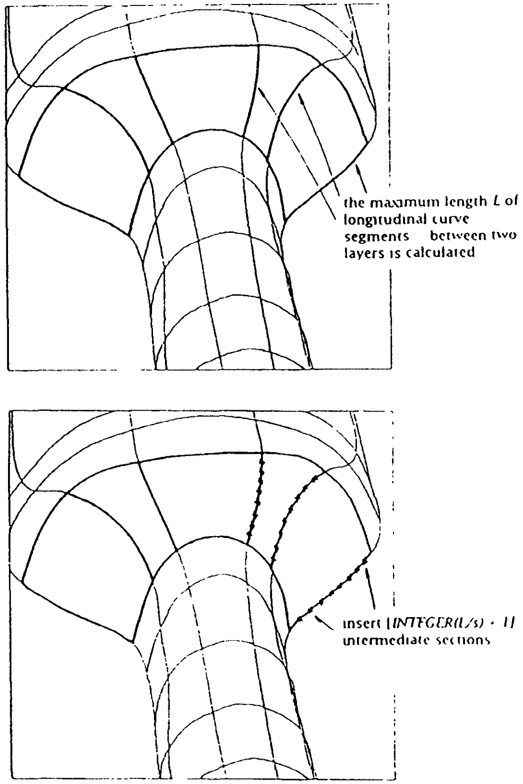

Fig. 7 Insertion of intermediate sections for finish machining

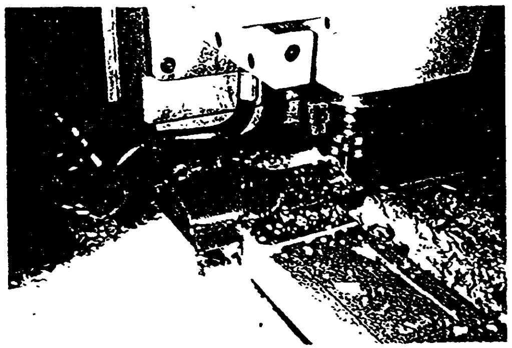

Fig. 8 A photograph of a bottle surface being machined