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Computer-Aided Design in Subtractive and Additive Prototyping

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ABSTRAK

Kertas kerja ini adalah berkaitan dengan penggunaan perisian komersil reka bentuk terbantu komputer di dalam reka bentuk dan manipulasi model kompleks untuk proses pemprototaipan penambahan dan pengurangan. Di dalam proses pemprototaipan pengurangan, perisian reka bentuk terbantu komputer digunakan untuk menghasilkan model permukaan. Model permukaan pula dipotong untuk menghasilkan beberapa lapisan muka keratan. Kemudian, model keratan akan ditukarkan daripada fail grafik ke fail bukan grafik (fail format berkecuali). Di dalam proses pemprototaipan penambahan pula, perisian reka bentuk terbantu komputer digunakan untuk menghasilkan model pepejal yang mempunyai beberapa rongga dalaman (model induk). Beberapa model pepejal yang mempunyai garis pusat yang berlainan dan lebih kecil akan dihasilkan daripada model induk itu. Model-model pepejal yang mempunyai garis pusat yang berlainan akan ditukarkan kepada model permukaan. Model-model permukaan itu akan dipotong dan ditukarkan kepada fail format berkecuali. Perisian reka bentuk terbantu komputer yang digunakan adalah AutoSurf, produk keluaran Autodesk, Inc. Komponen-komponen fizikal yang digunakan untuk melaksanakan proses-proses di atas adalah sebuah pengolah jitu robotik yang mempunyai empat darjah kebebasan (untuk memanipulasikan bahan mentah), suatu alat pengisar hujung yang berhidung bulat (untuk pemprototaipan pengurangan) dan suatu alat mengenap separuh cecair (untuk pemprototaipan penambahan). Kajian ini telah menunjukkan kemungkinan untuk menggunakan perisian reka bentuk terbantu komputer yang murah dan umum untuk menyempurnakan kerja reka bentuk model kompleks serta manipulasi kerja di dalam proses pemprototaipan dengan mengenepikan penggunaan perisian pemprototaipan cepat yang mahal.

ABSTRACT

This paper concerns the use of a commercially available computer-aided design software in designing and manipulating the complex-shaped models for subtractive and additive prototyping processes. In the subtractive prototyping approach, the computer-aided design software was used to create surface models. The models were section-cut into multiple cross sectional layers. Then, the section-cut models were converted from graphic files into non-graphic files (neutral format files). In the additive prototyping approach, the computer-aided design software was used to create solid models with internal cavities (parent model). Multiple smaller diameter solid models were then derived from the parent model. The various diameter solid models were converted into surface models. The surface models were then section-cut and later changed into neutral format files. The computer-aided design software used in the project was AutoSurf, a commercially available product of Autodesk, Inc. The hardware which was used in the above processes were a four degrees of freedom precision robotic manipulator (for manipulating raw material), a ball-nosed end milling device (in subtractive prototyping) and a semi-liquid deposition tool (for additive prototyping). This study revealed the possibility of using cheap and general computer-aided design software to accomplish the complex-shaped model design and manipulation work in the prototyping processes instead of using expensive rapid prototyping software.

Keywords: Computer-aided design and modeling, subtractive prototyping, additive prototyping

INTRODUCTION

A definition for Computer-Aided Design (CAD) is "the effective use of computer in creating, modifying, or documenting engineering design in any design activity" (Groover 2001). It is also a technique where man and machine are blended into a problem-solving team, intimately coupling the best characteristics of each (Besant 1983).

A computer-aided design system is comprised of (McMahon 1993):

1. The computer and associated peripheral equipment which are called hardware;
2. The computer programs which are called software that run on the hardware;
3. The data structure which is created and manipulated by the software;
4. Human knowledge and activities.

CAD systems often have large and complex computer programs, perhaps using specialized computing hardware. Normally, the software is comprised of the following elements that process the data stored in the database in different ways (McMahon 1993).

1. Model Definition – Adding geometric elements to a model of the form of a component is a typical example.
2. Model Manipulation – Moving, copying, deleting, editing or modifying the design model's elements.
3. Picture Generation – Generation of design model images on a computer screen or on some hardcopy devices.
4. User Interaction – Handling user's input commands and presenting output to the user about the operation of the system.
5. Database Management – Management of the files that make up the database.
6. Applications – Generating information of revaluation, analysis or manufacture.
7. Utilities – It is a 'catch-all' term for parts of the software that do not directly affect the design model, but modify the operation of the system in some ways such as selection of line type, display color, units and so on.

There are four important reasons for using a computer-aided design system to support the engineering design operation (Groover 1984):

1. Increasing Designer's Productivity – Designer can reduce time in operations like synthesizing, analyzing, and documenting the design because CAD can help him or her in conceptualizing the product and its components.
2. Improving Design Quality – Utilizing CAD system with suitable hardware and software capabilities allows the designer to produce a more complete engineering analysis and to consider a larger quantity and variety of design alternatives.
3. Improving Design Documentation – The graphical output of a CAD system is better than manual drafting in terms of quality of documentation. The engineering drawings are superior, and there is more standardization among the drawings, fewer drafting errors, and greater legibility.
4. Creating Manufacturing Database – Database for manufacturing a product is created in the process of product design documentation. Important manufacturing data like geometric specification of the product, dimensions of the components, materials specifications, bill of materials and others are documented in an engineering design.

Roughly 80% of a product's ultimate cost is determined and fixed during the design phase. Typically, companies only allocate about 5% of their resources on design and engineering. Contrasting these patterns of expenditure and commitment of resources over a product's life cycle, one can see that the five percent can have a great effect on competitive advantage (Orr 1987). A CAD system can have a significant effect on that

5% by increasing the effectiveness of the design and engineering tasks. CAD is not really used to reduce the percentage; it is used to come up with a better decision about the eighty percent of the product's cost and performance characteristics (Andersen 1993).

Some of the common and commercially available computer-aided design software programs are AutoCAD, Microstation 32, I/EMS, CATIA and MENTOR (Dorf 1994). The leaders in the mechanical CAD software arena are IBM, Computervision, Hewlett-Packard, Schlumberger, Autodesk, SDRC, EDS/Unigraphics and Parametric Technology (Zutshi 1993).

Prototyping

Prototyping has been one of the essential processes in the design and manufacturing cycle. Most of the time, a conceptual design has to be developed into a physical product so that the designers and engineers can rate its aesthetic features, validating its functionality, checking for specifications conformity, testing and optimizing the performance, planning the manufacturing processes and tools and marketing (Yan 1996). Prototyping can be categorized into subtractive and additive prototyping processes.

A subtractive prototyping process involves carving a solid block of material to reveal the shape of the desired object. In other words, material is removed from the raw part (Burns 1993 and 1994). Machining is the broad term used to describe removal of material from a work piece. Machining can be divided into the following categories (Sergeant 1991):

1. Cutting – Material is removed from the surface of a work piece by producing chips.
2. Abrasive – Material is removed from the surface of a work piece by producing tiny chips.
3. Non-Traditional – It utilizes electrical, chemical, thermal, and hydrodynamic to remove the material from a work piece.

Additive prototyping processes rely on making objects by adding one layer of material to another until the final shape is produced (Jacobs 1992). This idea is not new since model makers have used this method to make large wooden models for so many years (Frontera 1963). The method of building models from laminated wood avoids the gross distortion and cracking seen in models made from a single piece of wood. Laminations have also been assembled to make relief maps (Meyer 1967).

Various additive prototyping methods and machines have been developed to compete in the market. Five generic additive prototyping methods are stereolithography, laminated object manufacturing, selective laser sintering, fused deposition modeling and solid ground curing (Styger 1994).

The equipment, which was used in the prototyping processes, was a four-axes precision robotic manipulator and it was customized to handle cylindrical models (Tang 2000). In the subtractive prototyping process, a cylindrical raw material is held at both ends by the manipulator. The raw material is fed to a revolving ball-nosed cutter for material-removing process. In the additive prototyping process, a smaller cylindrical raw material is held at both ends by the manipulator. The raw block will be positioned under a semi-liquid deposition tool for the material-adding process. The side and plan views of the precision manipulator are shown in *Fig. 1*.

CAD Tool

The software used in the project was AutoSurf 3.2, a product of Autodesk, Inc. AutoSurf is a personal computer-based, two and three-dimensional mechanical design and drafting

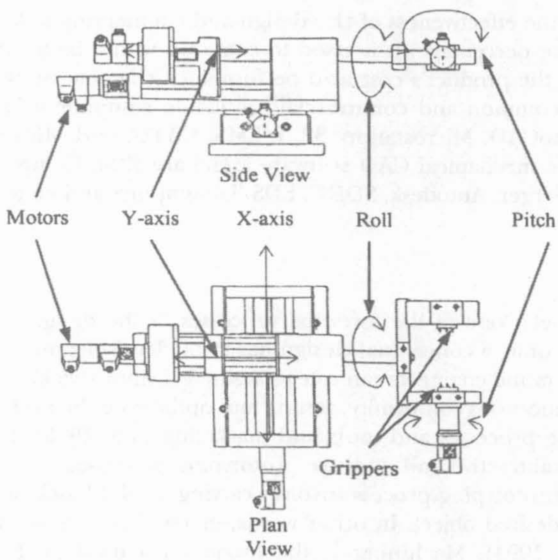


Fig. 1: Side and plan view of the precision robotic manipulator (Tang 2000)

software. Geometric shapes and figures can be created and modified for engineering purposes. A reduced instruction set processor (RISC), with a limited number of instructions is built into the processor to reduce the response time for running some applications on the software development system (Autodesk 1996).

Crosshairs and a computer mouse are used to locate geometric shapes within the work area. An X-Y construction plane is used for the two-dimensional mode that uses a three-point origin placed by the user, known as the user co-ordinate system (UCS). In default setting, the Z-axis is perpendicular to the personal computer screen and points directly to the user.

AutoSurf has an open architecture for easy customization of menus. The screen menu is the main menu, which includes the drawing editor, configuration, plot, file utility, and operating parameter menus. A dialogue box appears when a selected item is chosen from the pull-down menus to assist the user. Besides using the pull-down menus, the user can type in the commands into the command prompt to call up the functions.

The software commands are path dependent. For example, the 'undo' command will remove the screen image and any previous drawing layers up to the earlier drawing level. AutoLISP is the AutoSurf programming language that enhances the drawing and editing commands. It is an interpretive system, with instructions being read, interpreted, validated, and then executed in sequence. It can also be used to simulate the material processing process.

CAD for Subtractive Prototyping

It is important to know the physical limitation of the manipulator and the capability of the ball-nosed end milling process before attempting to create the surface models and the subsequent models modification. The criteria that must be followed in designing the surface models are:

1. Shape – Manipulation along the x-axis, y-axis and around the x-axis are used in this project. Hence, the shapes of all the surface models are in cylindrical forms.
2. Length – The three-pin grippers of the manipulator can hold a cylindrical block with the size ranging from 120 mm to 125 mm in length (by ignoring the protruding pin) and 40 mm to 150 mm in diameter. But, due to the protruding length of the pins that might obstruct the material removal process, the length of the surface model should be less than 110 mm.
3. Milling Depth – Maximum milling depth is determined by the length of the cutting edges. The length of the cutting edges along the cutter axis is about 15 mm. As a result, the distance between the surface model's highest and lowest co-ordinates (from the axis of rotation) should be less than 15 mm.
4. Reference Point – The model is a cylindrical surface form with a rotating axis at the (100, 100, 0). The x = 100, y = 100 and z = 0 is an important reference point for the CAM programs in the later stage. Motion parameters are produced based on the reference point.

Some of the important modeling configurations of AutoSurf need to be checked and set before creating the surface models. The configurations are:

1. Units – It is for selecting co-ordinates and angle display formats and precision. The selected type of unit is Decimal and the precision is up to four decimal points. The selected type of angle is Decimal Degrees and up to 0° precision. Direction of rotation can be set under this command. East has been set as 0.0° and the direction of rotation is counter clockwise.
2. Drawing Limits – It is for setting and controlling the two and three-dimensional drawing boundaries. The lower left corner of the drawing limit is set at (0.0000, 0.0000) and upper right corner of the limit is set to (297.0000, 210.0000). A4 size's drawing limit was set.
3. Layers – The user can set as many line types and line colors as possible so that they can be used in the subsequent modeling.
4. Drawing Aids – This will enable the user to set Grid spacing and Snap spacing that will make the modeling easier.
5. Preferences – It is for customizing the AutoSurf settings. It can be used to set the types of digitizer input, font type, font size, background color and others.

The AutoSurf modeling system is based on NURBS (non-uniform rational B-spline) curves. Models can be created and modified by using functions like Draw, Modify and Surface Create. The Draw function enables the creation of line, polyline, arc, circle, ellipse, polygon and point. The Modify function has commands like move, copy object, offset, mirror, array, rotate, scale, trim, extend, edit polyline, chamfer, fillet, union, subtract, intersection and erase.

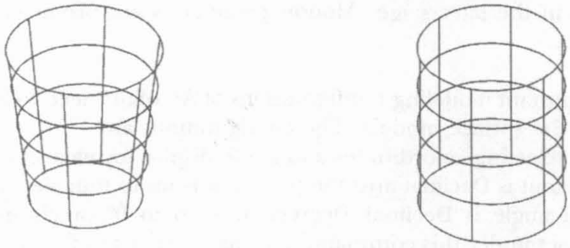
There are various commands under the Surface Create function. There are four different types of surfaces in terms of the methods used to construct them:

1. Surface Primitives – Created directly by the AutoSurf and the examples are cone and cylindrical surfaces.
2. Motion-based Surfaces – Produced by moving wires through space. Examples are revolved, extruded, tubular and swept surfaces.
3. Skin Surfaces – Constructed by applying over a wireframe such as ruled surface.
4. Derived Surfaces – Generated from the existing surfaces like blended surface.

Primitive surface models do not require a wireframe for their construction but are instead directly created using the user-specified values. Primitive cone and cylindrical surface models are shown in *Fig. 2.*

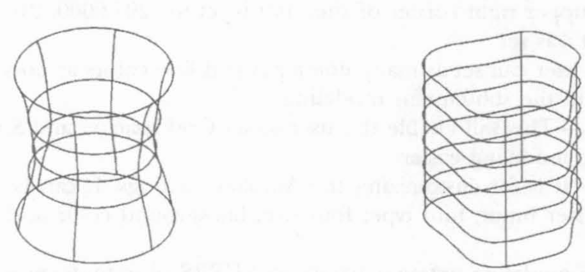
Motion-based surface models are created based on the three-dimensional motion of wires through space. Rotating any number of path curves or profiles around a selected axis creates revolved surface models. Extruded surface models can be created by moving any three-dimensional wire shape along a straight line. Four types of motion-based surface models are shown in *Fig. 3.*

A blended surface is one of the derived surfaces. It is created between two, three, or even four other surfaces. The blended surfaces are tangent to the surfaces from which they are created. Blended surfaces may also be created between wires or between combinations of wires and surfaces. Blended surface model is shown in *Fig. 4.*

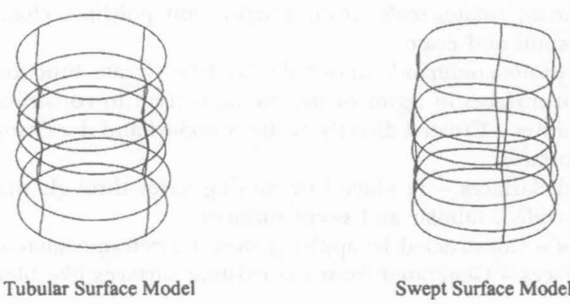


Primitive Cone Surface Model **Primitive Cylindrical Surface Model**

Fig. 2: Primitive cone and cylindrical surface model (Tang 2000)

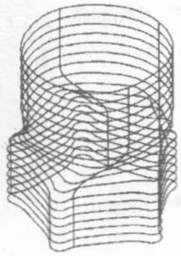


Revolved Surface Model **Extruded Surface Model**



Tubular Surface Model **Swept Surface Model**

Fig. 3: Motion-based surface models (Tang 2000)



Blended Surface Model

Fig. 4: Derived surface models (Tang 2000)

Ruled surface model is one of the skin surface models. Skin surface models are created by "skinning over" a wireframe shape. Skin surface models can be visualised as a surface draped over, or skinned, across an existing wire structure. Ruled surface models can be constructed from only two path curves. The path curves can be lines, arcs, closed or open polylines. Some ruled surface models are being shown in *Fig. 5*.

Of all the surface models described above, only the ruled surface modeling method was selected for the project due to its sophistication and versatility. Cone, cylinder and revolved surface models are symmetrical models. Although extruded, tubular and swept surface models are not symmetrical, but they are simple. Blended surface model is not suitable since the distance between the highest and lowest point (from the axis of rotation) of the surface is unpredictable. The milling depth might need to be more than 15 mm in some cases. Ruled surface model is the best method for creating complex surface model because such models are asymmetric, complex and have predictable milling depth.

Two or more polylines were used to create the ruled surface models in the project. The shapes of the polylines were circle, heart, complex, star, pentagon, cross and square. After creating the surface model, the subsequent step is to cut it into multiple cross-sectional layers. Only the neutral format file (DXF entities file) of the section cut surface model contains the useful data for the subtractive prototyping process. The Surface Create function is responsible for the section-cut operation. In order to cut the surface model, the following information must be provided.

1. Section type – It is for selecting Single, Parallel or Radial sectioning cut.
2. Initial plane – It is for specifying the initial cutting plane. It can be either from the user View Direction or UCS (user co-ordinate system) plane.
3. Multiple cuts – When Parallel or Radial section type is selected, the user needs to specify the Stop position of the last cut and the Step of each cut (step over).

Examples of the section cut surface models are shown in *Fig. 5*.

CAD for Additive Prototyping

It is important to know the physical limitation of the manipulator and the proposed additive prototyping equipment before attempting to create the solid model and the subsequent models manipulation. The criteria that must be followed in designing the solid model are:

1. Shape – The proposed additive prototyping equipment is a vertical semi-liquid deposition device. The semi-liquid material will be deposited onto the rotating

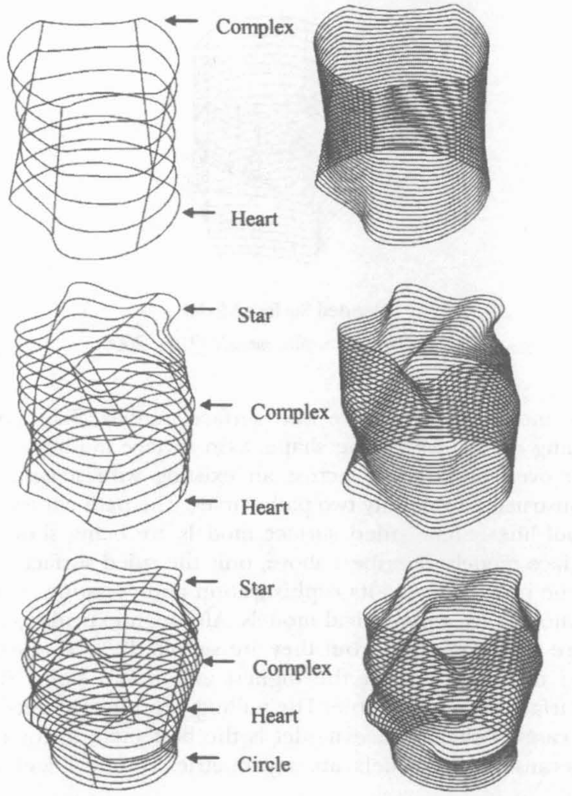


Fig. 5: Ruled surface and section cut surface models (Tang 2000)

cylindrical core material held by the grippers. As a result, only manipulations along and around x-axis are used in handling the model. Hence, the shapes of the solid model should be in cylindrical form.

2. Length and Reference Point – Same criteria as the CAD for the subtractive prototyping process because the maximum length of the model and the modeling reference point are the same.

Some of the important modeling configurations of AutoSurf need to be checked and set before creating the solid model. The configurations are:

1. Units, Drawing Limits, Layers, Drawing Aids and Preferences – Same configuration as the CAD for the subtractive prototyping process.

A solid cone model was created by using AutoSurf by revolving a polyline around an axis. Then, four internal cavities were created in the solid cone by using the Boolean operator's subtract function. The solid cone with four internal cavities is called the parent model. The parent model is shown in *Fig. 6.* Later, multiple smaller diameter solid models were derived from the parent model by using the Boolean operator's intersection function. The smaller diameter solid models were then changed into surface models. Both ends of the surface models have to be deleted. The surface models

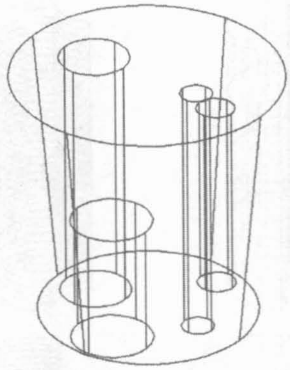


Fig. 6: Solid model in wireframe representation (Tang 2000)

went through the section cut process to become section-cut models. Only the section-cut models can be converted into useful neutral format files. Some of the derived surface models and section-cut models are shown in *Fig. 7*.

There is no one step command in creating a solid cone. A solid cone model can be created by revolving a closed polyline. Four points were used to create the close polyline. The x, y and z co-ordinates (x, y, z) of the points were (100, 100, 0), (100, 200, 0), (50, 200, 0) and (60, 100, 0). The axis of revolution started from (100, 100, 0) and ended at (100, 200, 0). The angle of revolution was a full circle. The solid cone model was then rotated in three-dimensional round x-axis at (100, 100, 0) with 90 degrees of rotation angle. After that, four solid cylinders were built inside the solid cone model. Subtract command was used to subtract the cylinders from the solid cone model. In the end, the solid cone model had four internal cylindrical cavities.

Eight smaller diameter solid models were derived from the parent model. The eight derived models' maximum diameters are 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm and 90 mm. Intersecting various diameter solid cylinders with the parent model will create the eight models. Once again, Boolean operator of Intersection was used in deriving the smaller models.

The derived solid models and the parent model were then converted into surface models. After obtaining the surface models, the top and bottom surfaces of each model were deleted. The surface models then went through the section-cut operation. The section-cut type was parallel, UCS was the initial plane, the step over distance is 3 mm and it will stop at the height of 99 mm. So, every surface model was section-cut into 34 layers.

DISCUSSION

AutoSurf was used in this project for producing ruled surface models and solid models with internal cavities. AutoSurf was also used in changing the solid models into surface models. And, AutoSurf has the capability to produce the section cut surface models from the surface models.

AutoSurf is a very powerful and user-friendly CAD modeling software. It has completely outdone the AutoCAD, its predecessor. As far as the project is concerned, AutoSurf provided all the CAD requirements for the project. It has the internal pre-processor to change the model graphic file into a good and simple neutral format file – DXF entities file.

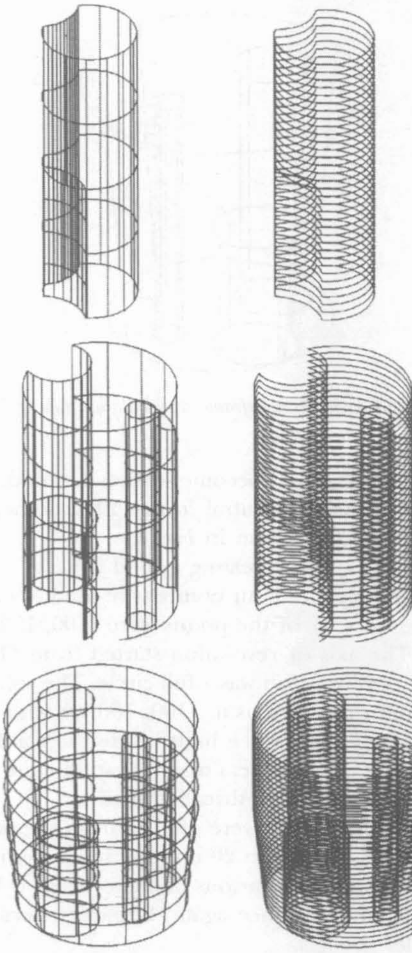


Fig. 7: The derived surface and section cut models (Tang 2000)

The step over distance of the section-cut feature in the AutoSurf will determine the amount of section-cut layer of the model. More than 400 co-ordinates in each section-cut layer were generated by the AutoSurf. The surface roughness and the accuracy of the physical product are directly proportional to the amount of co-ordinates in each layer and the quantity of layers in the section-cut model. If the layer quantity is high, then the accuracy is better and the surface is smoother. If the point quantity is large, then the product will be more similar to the design CAD model.

The amount of surface data was found to be adequate by examining the quality of the milled product. The overall model production time and the dimensional accuracy of the models are affected by the section-cut parameter as well. The dimensional comparison (measuring the diameter of the first section-cut layer) between the designed and production models revealed the average percentage of error to be 0.37%.

CONCLUSION

The procedures for surface modeling and manipulation for the subtractive prototyped models were revealed. The methodologies for creating the solid model and the subsequent model manipulation for the additive prototyped models were described. The study has shown that prototyping can be accomplished with the use of a cheap and general CAD software instead of an expensive rapid prototyping software.

Besides, the researchers developed effective procedures for the production of NURBS surface data from three-dimensional solid and surface models. The three-dimensional model has to be converted into a surface model (if the original model is a solid model) before it is section-cut into multiple cross-sectional layers. The distance between the section-cut layers (step over) will determine the surface finish of the end product. The precision accuracy of the step over distance can be set to as high as sixteen decimal points. Then, the section-cut model is changed into DXF entities file for further data processing. Thus, another way of producing NURBS surface data was developed.

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