A Customized Smart CAM System for Digital Dentistry

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ABSTRACT

This paper presents an automated system for NC tool-path planning and generation of digital dental restoration. The process planning of an automated system has to do with well-ordered approaches, and accurate, efficient manufacture of work-pieces or parts, from initial to finished stages. Traditionally, dental restoration making is a totally manual and labor-intensive work, and the computer aided design (CAD) / computer aided manufacturing (CAM) technology has rarely been utilized. In recent years, however, with the advancement of intra-oral scanning technology, more and more CAD/CAM technology is being applied to the design and production of dental restorations. Since the operators are dental technicians who are mostly unfamiliar with CAD/CAM, it is important to have a customized and highly automated dental CAD/CAM system for the digital dental industry. General-purpose CAM system cannot be used in this case because long hours of tool-path programming and editing are required. In order to reduce processing and editing time, a highly customized and "one-button" CAM system is developed in this work to reach automation and increase efficiency. The key is to capture and incorporate the domain knowledge of dental design and production into the tool-path programming process. In other words, the complicated process planning problem can be overcome by a knowledge-based approach, and the resulting machining plan can be realized by a 5-axis milling machine to directly produce dental restorations. In this paper, we show that machining sequences of several different dental restorations, from simple to complex, can all be automatically planned and produced by the proposed system. A comparison between the automated system and the traditional manual approach is also presented and discussed.

Keywords: digital dentistry, NC tool-path generation, CAM, machining.
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1 INTRODUCTION

The objective of developing an automated machining process is to reduce the time and cost of production through increased automation. When planning the machining process, it is important to consider: the choice of product design data, selection of the machining process and tools, determination of the fixtures and datum, sequence of the operations, determination of the proper cutting parameters, tolerance and generation of the tool-paths and exportation of the NC data [1].

Recent developments in oral cavity medical services have tended towards the reduction of patients' treatments. To save time and maintain high degrees of accuracy, the design and manufacture of dentures has gradually changed from the impression or lost-wax casting process to digital CAD/CAM technology. The time requirement of the traditional process of tooth molding, from taking the initial impression to production, is about six hours, as shown in Fig. 1. In this process, the quality of the product is inconsistent. However, in the new process of tooth molding, it is based on digital procedures, and the production can be accomplished faster than the traditional processing time, as shown in Fig. 2. Such a process reduces the number of mistakes and allows for consistent quality of the product.

Fig. 1: Traditional process of tooth mold: (a) Impression, (b) Creation of wax base and sculpturing the shape, (c) The lost-wax casting process, (d) The Sand blasting process, (e) The polishing process.

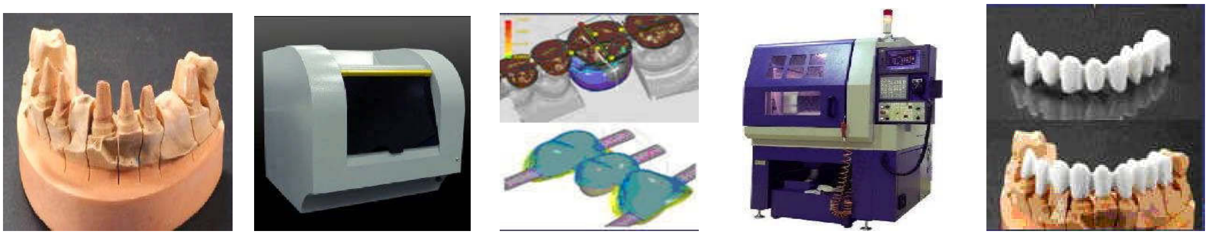


Fig. 2: Digital process of tooth mold: (a) The working model, (b) The digitization process, (c) The CAD/CAM reconstruction process, (d) The milling process, (e) The final product.

The lost-wax casting process is limited by the fact that metal is the only material that can be used. Further, during the process, it is easy for bubbles to form inside the product which leads to a rough surface that needs finishing. In contrast, the CAD/CAM system allows far greater flexibility as materials such as zirconia or titanium can be used. The quality of the surface is also better due to the machining process.

However, in a general CAM system, there can be inconsistent quality, due to the fact that individual operators each design and control their own machining sequence. The challenge is to develop a manufacturing procedure that is well-ordered, consistent and reduces the need for reworking. The automated system which combines computer-aided manufacturing and process can play an important role in achieving the requirements of automation. In this paper, the use of an automated system to reduce processing time and increase efficiency is proposed.

2 RELATED WORK

2.1 Computer Aided Process Planning (CAPP)

The idea of developing process plans using computers was first presented by Neibel. In 1976, the first variant system, called CAPP, was developed under the sponsorship of Computer Aided Manufacturing International (CAM-I) [1]. There are two basic approaches to computer aided process planning - variant and generative [2]. More recently, research efforts on CAPP have shifted to feature recognition [3], STEP-based product models [4], and intelligent process planning based on the capacity profile of machine tools [5]. The common objective is to effectively generate stable, precise, and flexible process plans. In the application of the CAPP/CAM integrated system, C. Chung and Q. Peng [6] described that the selection of tools and machines can be matched through web-based manufacturing environments. B.K. Choi and K. Ko. [7] presented a C-space-based CAPP system. Using this system, the free-form die-cavity machining can be realized.

2.2 Machining Strategy

Once a series of machining processes is completed, the raw material becomes a finished product. Generally speaking, these processes can be classified according to roughing processes and finishing processes. The machining strategies used, including the projection strategy [8], z-level strategy [9,10], pocketing strategy [11-12], and clean-up strategy [13,14], differ according to the machining requirements. The machining operations required for different tooth types can be set up by combining various strategies with tool parameters.

2.3 Simulation

In the past, NC simulation can be categorized into three major methods [15]. The first method uses direct Boolean operations of solid models to calculate the volume of material removed during the machining process [16-17]. The second method uses spatial partitioning representation to define a cutter and the work-piece [18]. In this method, a solid object is decomposed into a set of geometric elements such as a Z-map (Z-buffer), voxel or adaptive voxel data structure [19] representation, thus simplifying the Boolean operations. The third approach uses discrete vector intersection [20]. Machining is simulated through cutter path envelopes by calculating the intersection between the points of a surface and the vectors. In this paper, the method of simulation and collision avoidance described in the following sections belongs to the second category.

3 SYSTEM OVERVIEW

In this paper, we standardize the preparation and production processes to develop an automated system for tooth molds. In Section 4, we elaborate on the components of an automated system, including the generation of the auxiliary features, the machining strategies, the restoration of cutting parameters, the uncut area detection, and the uncut area removal. In Section 5, the automated system used in the coping or crown of a tooth will be presented. In Section 6, some examples of the tooth models that were tested and verified will be given. Our conclusions and possibilities for future research will be put forward in Section 7.

4 THE COMPONENTS OF THE AUTOMATED SYSTEM

Because there is not much difference between the construction of copings and that of crowns, it is possible to use the manufacturing process with the same automated program. It is always important to reduce human labor as much as possible and to aim for the maximum savings in both time and cost. Increasingly it is being recognized that these goals can be achieved by standardizing and automating the tooth manufacturing process.

This automated system includes three major parts: (1) Pre-machining associated arrangement which includes the set-up of processing coordinates systems and the size of raw materials. (2) Tool-path associated arrangement which includes loading and executing the cutting parameters and machining strategies and computing gouge-free tool-paths. (3) Undercut associated arrangement which includes auto-detecting the regions of undercut and adopting suitable machining strategies. Details are described as follows:

4.1 Pre-machining Arrangement

The goal of this stage is to automate the preparation for machining. This means that the orientation of the work-piece and the auxiliary features related to computer-aided design (CAD) can be automatically set up and generated before tool-paths are calculated. This will establish the basis of further computation.

First, after the STL or surface model has been imported, the working foundation of the coordinate system will be located in the center of the work-piece. The required raw materials would be automatically computed. Information of the tooth-axis will also be obtained from the importation of the model. The support bar of the tooth model would be created along the parallel y-axis of the tooth-axis to support the model; to keep it stable and prevent it from falling during machining. Finally, after the machining is complete, the product can be taken down by breaking the bar, as shown in Fig.3 (a).

Fig. 3: The (a) Support bar, (b) Lingual type and (c) Ring-like type of support walls of tooth bridge.

Breakage can occur when long tooth bridge (using brittle materials such as zirconia) are sintered; this is caused by uneven stress inside the long bridge. The problem can be solved by adding a support wall when sintering; There are two types of support walls: lingual and ring-like, as shown in Fig. 3 (b)-(c).

To solve problems caused by machining constraints such as cutting–load or collision, the surfaces of auxiliary features need to be created to avoid breakages when machining with zirconia. The steps required are as follows:

- The first step is to create the maximum profile of the tooth model at the periphery of this model, as shown in Fig. 4(a).
- The second step is to calculate the boundary curve A by using the maximum 3D profile, offset in an ascending direction. Boundary curve B is calculated from curve A, using the working cutter radius as 3D offset radius, as shown in Fig. 4(b).
- The third step is to calculate boundary curve C by using the maximum 3D profile, offset in a descending direction. This is used to calculate boundary curve D, using the working cutter radius as 3D offset radius, as shown in Fig. 4(c).
- The final step is to create two surfaces of auxiliary features, using the two pairs of curves – boundary curves A&B and boundary curves C&D, as shown in Fig. 4(d). The auxiliary surfaces can be represented in NURBS form as shown in Eqn. (1).

$$S(u,v)=\frac{\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u)N_{i,q}(v)w_{ij}P_{ij}}{\sum_{i=0}^{m}\sum_{j=0}^{n}N_{i,p}(u)N_{i,q}(v)w_{ij}}\text{, and }\begin{cases}N_{i,p}(u),\ N_{j,q}(v):\textit{basis functions}\\ P_{ij}\ :\textit{control points}\\ m,n\ :\textit{number of control points}\\ w_{ij}\ :\textit{weights}\\ u,v\ :\textit{parameters}\end{cases}\qquad(1)$$

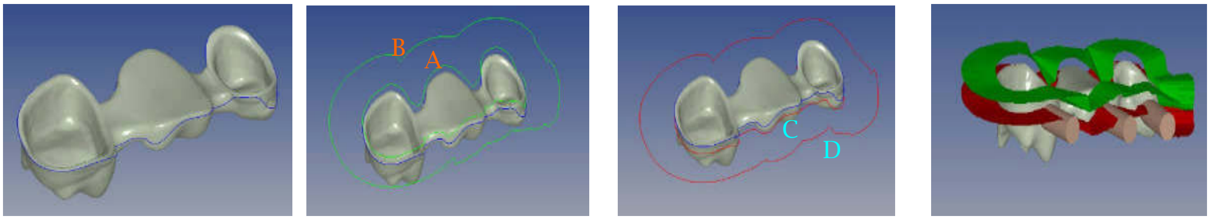


Fig. 4: The creation of two surfaces of auxiliary features: (a) Creation of the maximum profile of the tooth model, (b) Creation of boundary curves A and B, (c) Creation of boundary curves C and D, (d) Building the surfaces of auxiliary features.

4.2 Tool-path Planning and Generation

The aim of tool-path generation is to approximate the design part using a number of polylines. Ideally, every point of the polylines will fall on the surface of the design part (or is deviated from the surface with an allowable tolerance), and a cutter will be commanded to move through these points in space. The full tool-path generation process need to consider three components: (1) cutter selection (2) machining stage (rough cut, finish cut, etc) (3) tool-path topology pattern design.

An indispensable aspect of an automated system is the need to undertake collision detection before machining. When calculating tool-paths, the length and shape of cutting tool will often not be considered and, therefore, the collision between the cutting tool and the tooth model needs to be prevented. For collision detection before machining, octree-based voxel representation and the concomitant algebraic equations are used to model the work-piece and the automatically programmed tool geometry (APT) [15]. The octree-based voxel representation of the work-piece provides simulation accuracy but does not require much memory space. Therefore, the implicit algebraic equations can represent a universal cutter with great precision. The gouging detection is performed by comparing the implicit algebraic equations of APT with the original surface model. After the gouging detection, a series of tool-paths can be exported safely.

4.3 Undercut Arrangement

The undercut area referred to here is that area which can not be machined when using traditional 3-axis machining. Because the shape of the denture has irregular distribution, part of the denture will appear to have undercut areas, and the leftover residual will cause the problem of unfit teeth.

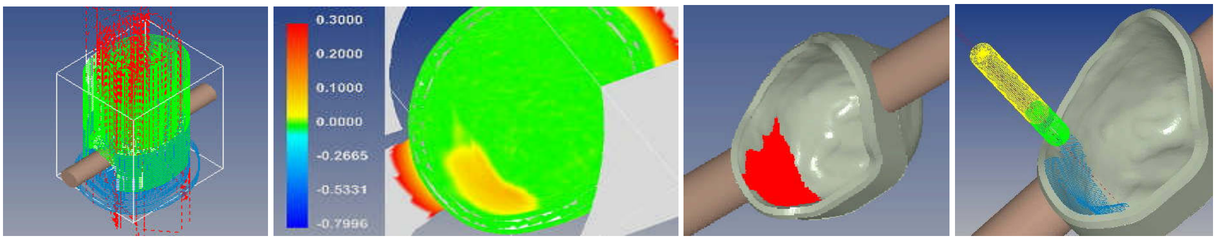
The steps taken to dealing with the undercut region are:

- The first step is to generate all the tool-paths required for the machining sequences.
- The second step is using the method mentioned in Section 4.2 to undertake numerical control (NC) simulation/verification. The error analysis can be performed by comparing the result of simulation with the original surface model, and the tolerance is calculated using Eqn. (2) and (3). The triangles of the surface model will be labeled ‘uncut’ if the amounts of undercut exceed the threshold after error analysis.

$$\varepsilon = \left|P(x,y,z) - S(u,v)\right| = \min \quad, and \quad \begin{cases} \varepsilon, x, y, z \in R \\ u, v \in [0,1] \end{cases} \qquad \text{for surface model} \qquad (2)$$

$$or \quad \varepsilon = \frac{|ax + by + cz - d|}{\sqrt{a^2 + b^2 + c^2}} = \min \quad, and \quad \varepsilon, x, y, z, a, b, c, d \in R \qquad \text{for STL model} \qquad (3)$$

- The third step is to form a 3D boundary curve after creating the maximum profile of those triangles labeled ‘uncut’.
- The final step is to find the optimal working coordinate system by using the statistical sampling, and generating tool-paths inside the boundary curve, as shown in Fig. 5.



(a) (b) (c) (d)

Fig. 5: The procedure for dealing with undercut areas: (a) Tool-path calculation, (b) Simulation and error analysis, (c) Undercut areas calculation, (d) Machining strategy applied to the undercut area.

5 INTRODUCTION TO THE AUTOMATED SYSTEM

The automated system includes the automated generation of the auxiliary features, the automated processes for machining strategies, the automated generation of the uncut areas and tool-paths, and the automated protection of collision, as shown in Fig. 6.

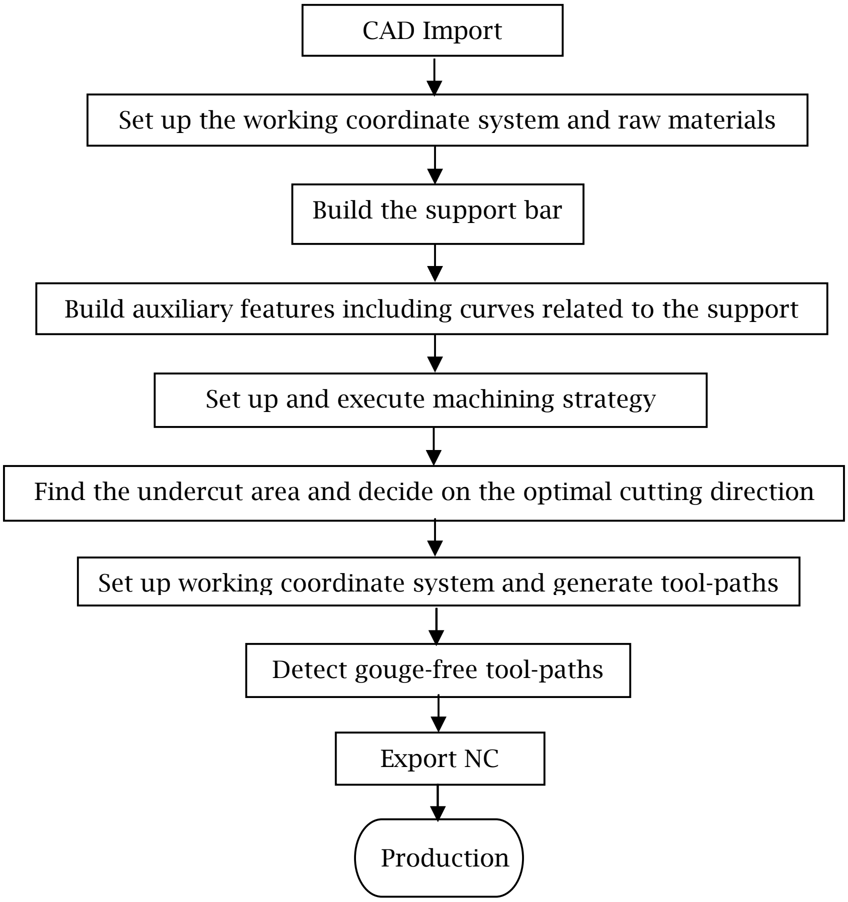


Fig. 6: The flow chart of proposed processes for automated.

The auxiliary features include the creation of the support bar and the creation of auxiliary surfaces and curves. The auxiliary features also help to make the calculation of tool-paths more logical and efficient. The processing strategy can be set up by using the default machining parameters and the correspondence between the model data and cutting parameter of each machining strategy can be loaded completely using the existing database. The cutting parameter of each machining strategy is loaded, associating the CAD data with the level and color management. The recorded information can be imported correctly to each machining strategy, as shown in Fig. 7(b). After the processes of simulation and error analysis, the auxiliary boundary curves of uncut areas can be created and the machining strategy applied accordingly to these areas. An integrated machining system will not be complete without a gouge-free module. Therefore, the detection of collision between the CAD model and the APT is executed in order to guarantee the safety of tool-path generation.

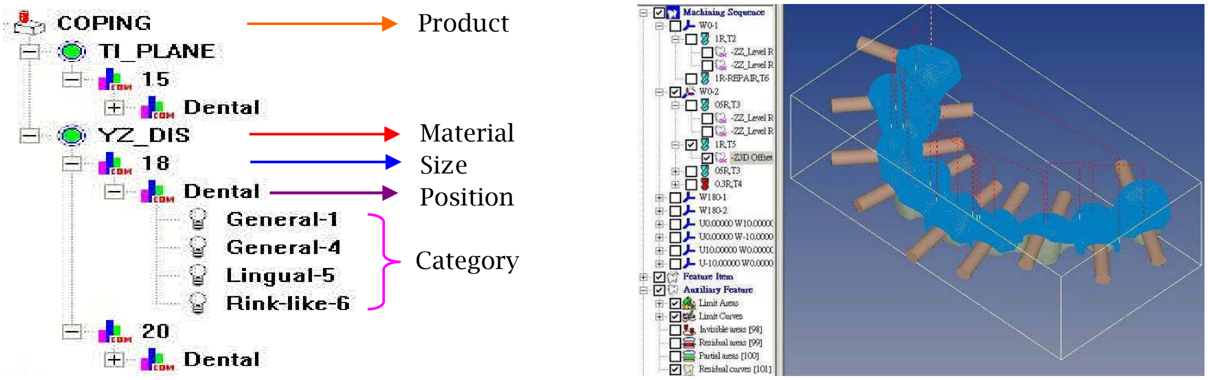


Fig. 7: The proposed CAPP system: (a) One kind of the database structure, (b) The result of automatically loading machining strategies and cutting parameters, and then generating tool-paths.

The proposed system provides a "batch" operation to implement suitable planning, from importing the CAD model to exporting the NC code, for various kinds of tooth models such as coping or crowns. This operation requires minimal effort; the user only needs to insert the files containing tooth models and the database into a specific folder. The auxiliary features and gouge-free tool-paths are planned and created by the system. An automatic calculation server can be set up using the "batch" operation. The operation is time-saving and the manufacturing process can be standardized even though each individual tooth is different. Most importantly, the process planning is automated and will not vary from person to person and the quality of production can be maintained.

6 IMPLEMENTATION AND DISCUSSION

In a general CAM system, there are many actions which require manual skill and experience. The creation of auxiliary features requires an operator with an attentive mind to avoid operational mistakes and machining problems. However, because the shape of a tooth model is complex, there will always be some inconsistency in quality. This is despite high levels of concentration and patience during the design of the machining strategy, and is due to the fact that there will always be differences in tool-path generation according to the varying skill and experience of the operator.

The following gives three cases of complex tooth restorations, and their manufacturing processes which were automatically planned and standardized by the proposed system were applied in real dental practices. In order to verify the proposed system, NC tool-paths were generated for these three tooth models. These CAD models are in STL format with different materials such as zirconia and titanium, and the tool-path contains roughing and finishing sequences using different types of cutter and different machining sequences.

These three STL models contain 67682, 72920 and 121464 triangles in each case. Their respective sizes were 13 × 13 × 15 mm, 17 × 15 × 18 mm and 17 × 33 × 18 mm. The information of three tooth models is listed in Table 1.

	Case 1	*Case 2*	*Case 3*
Material	Titanium	Zirconia	Zirconia
Product	Coping	Crown	Bridge
STL	67682	72920	121464
Size (mm)	13 × 13 × 15	17 × 15 × 18	17 × 33 × 18

Tab. 1: Information on the three tooth models.

Because the shape of the denture resulted in irregular distribution, there were still some undercut regions after machining was completed. Thus, an additional machining strategy was required, such as clean-up or area-cut, to machine these areas well. The automated generation of the support bar, the auxiliary features, aspects of the machining strategies and the final different productions of these three cases are shown in Figs. 8, 9 and 10.

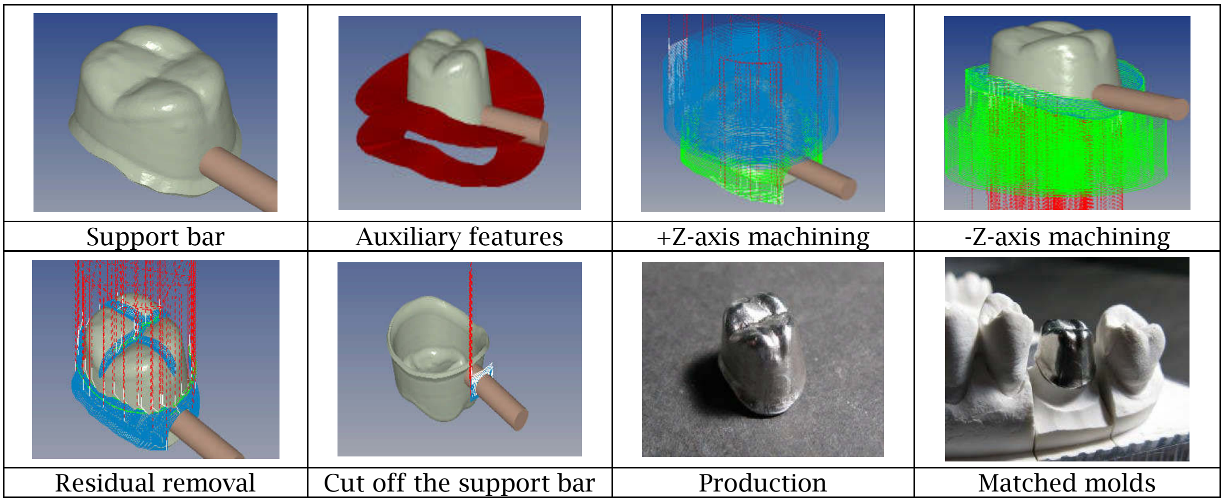


Fig. 8: Using the proposed system on the coping case.

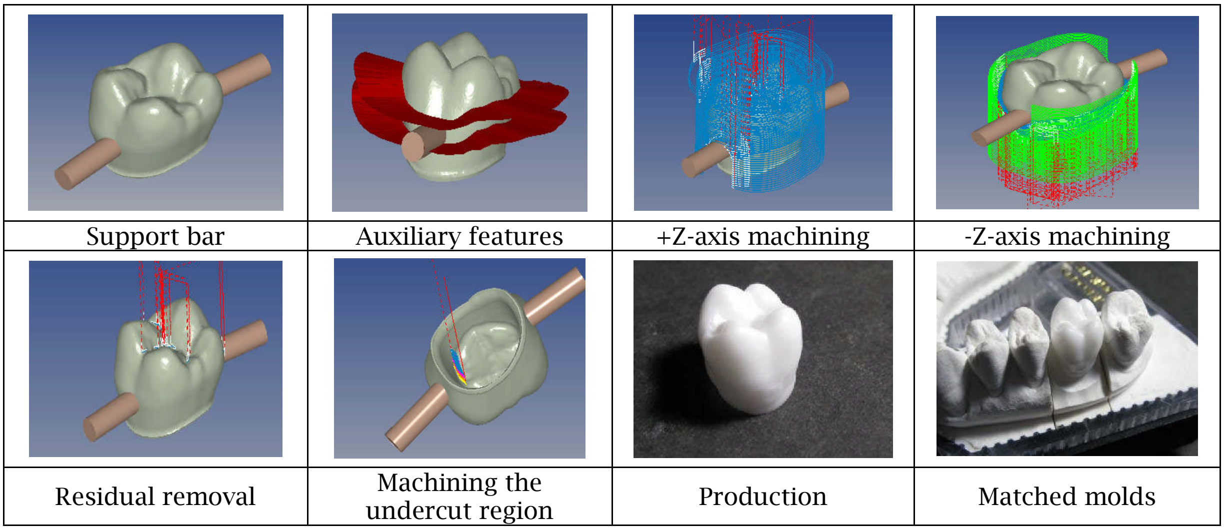


Fig. 9: Using the proposed system on the crown case.

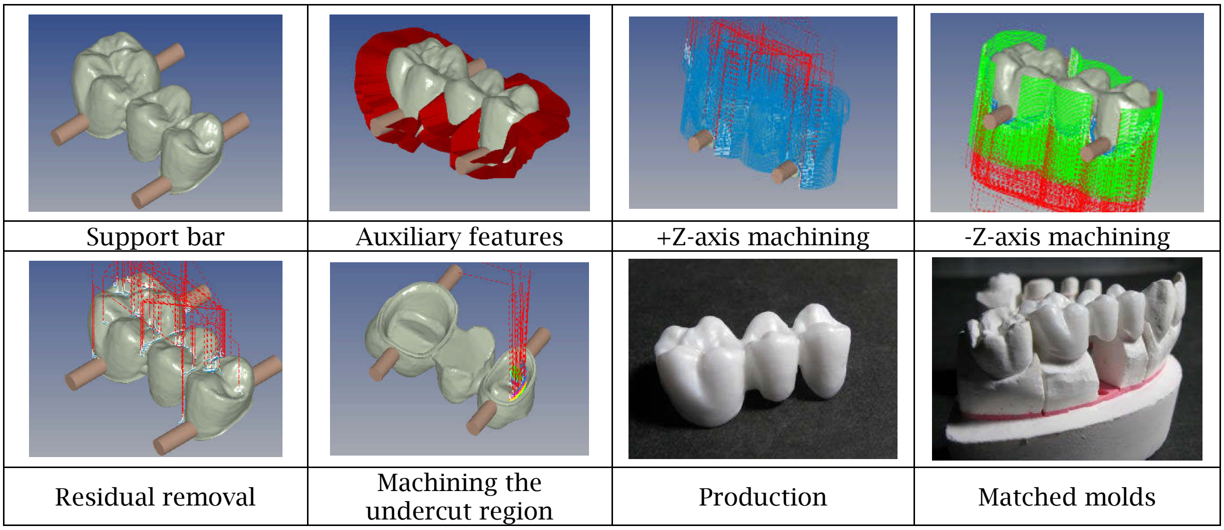


Fig. 10: Using the proposed system on the three-unit bridge case.

The traditional process of denture making by tooth mold produced from impression to casting and veneering needs a great deal amount of manual work. The process can easily fail due to the lack of experience or skill. Centralized mass production of individualized teeth by pure manual labor is also difficult. But now the digital design and manufacturing approach avoids the mistakes of manual operation and makes mass customization possible. It completely changes the dental industry and now dental labs can make customized teeth at a remote distance through the use of internet. In a foreseeable near future the digital process will replace the traditional manual process of making dental restorations. A comparison between a traditional and digital system is shown in Table. 2.

Item / *Process*	*Degree of Manpower Involved*	*Accuracy*	*Reproduction Quality*	*Time of Manufacturing*	*Time to Repair and Maintain Product*
Traditional Process	High	Low	Low	Long	Long
Digital Process	Low	High	High	Short	Short

Tab. 2: A comparison between a traditional process and the proposed system (digital process).

7 CONCLUSION AND FUTURE WORK

In order to reduce manual programming and editing time, this paper proposed the use of automated procedures to reduce processing time and increase efficiency. Through the capture of the domain knowledge, a very complicated process planning problem can be overcome. An automated manufacturing process can simplify and replace the manual operating sequence. Thousands of dental restorations have been generated in this way, supporting the thesis that this approach is feasible.

From the CAD model importing in the beginning to the NC code exporting in the end, many manual operations, such as generating auxiliary features or setting up machining strategies and parameters, are needed. Through the proposed approach in this paper, the manual process can be converted to a standardized automatic process, and the objective of quick production and consistent quality using automatic procedures can be achieved successfully.

Because the CAM processes are detailed and complicated, we have focused on the automation of this part and developed the automated process to resolve this problem. With regard to CAD there are still some issues regarding automation. The generation of the gingival margin line and the decision of tooth-axis are examples of aspects that still need to be researched in order to make the automated design process more comprehensive [21].

In the future, work can include the conversion of more types of dental products (such as implant abutments and bars) to a standard manufacturing process. Likewise, new algorithms and machining strategies must be developed to aid the adaptation of new automated systems to these new products.

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