Applying Signal Processing Techniques to Facilitate Shape Modeling in Industrial Design

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Abstract: In this paper, applications of signal processing techniques in facilitating shape modeling in industrial design will be explored. The theoretical principles will be simply revisited, and our focused attention will be given to the application examples of using the proposed techniques to promote the efficiency of industrial design. These examples will demonstrate that, by enabling the abstract and reusing of the regional shape information, the proposed techniques are effective to support rapid shape conceptualization, creation, and manipulation.

Key-Words: Freeform feature reuse, signal processing, shape modeling, Fourier transforms.

1 Introduction

Design reuse widely exists throughout the design process in the form of providing competitive product strategies, alternating design concepts and configurations, and rationalizing design implementations [4]. Shape reuse is one of the pivot aspects in the broad area of design reuses in industrial design, which often refers to as the reuse of geometric information, such as geometric parameters, patterns, and topological configurations. During the past decades, with the widespread application of CAD/CAID systems and digital acquisition equipments, a tremendous amount of design knowledge has been accumulated as diverse repositories of product models on the Internet or within organizations. The exploitation of this valuable resource, especially that of geometric models of products, has become an attractive yet challenging research field to the community of design research, for its merits leading to saving time and money, and avoiding unnecessary mistakes [1] [2] [3].

Freeform feature (FFF) reuse was recognized one of the effective means to achieve shape reuse [5] [6]. However, how to capture the information content of a shape remains as a challenge in implementing shape reuse, especially in shape modeling in industrial design, where diverse model formats can be involved.

2 Related Works

Conventionally, feature reuse is implemented in *the spatial domain* by transferring a regional geometry from one place to another within a model or cross models [6] [7]. A post-processing, such as a context adaptation and a boundary transition, has to be associated with the implementation process in order to incorporate the reused geometry into the new modeling context. For instance, the copy-and-paste method has implemented a FFF reuse by first cutting-and-copying the feature geometry and then pasting it on a specified region of the target surface [7] [8]. In this context, feature retrieval is carried out by detecting the curvature variation along the feature boundary [9]. This can be rather sophisticated, and resulting in that the existing approaches rely heavily on the underlying data structure of the model [10] [11]. These methods may work with all kinds of digitized shape models, including solid models, surface models, mesh models, and point cloud models. In particular, when working with discrete models, feature-fitting techniques are often employed to serve as an auxiliary means to discriminate the feature geometry and to interpolate it into a continuous representation [12]. In some cases, feature-fitting techniques are even indispensable to the reuse of a regional geometry, for instance, when there is a need to manipulate a FFF with a few high-level parameters during reuse in the product shape styling or modeling process.

However, one of the main drawbacks of the existing approaches is that they are unable to eliminate the distortion of the regional feature imposed by feature interactions during the creation process. For instance, in case a feature was located on a curved surface, the existing methods are typically unable to separate the feature from the domain shape.

We have developed the signal processing-based techniques for FFF reuse. In the paper, we will revisit these techniques, and explore their applications in facilitating shape modeling in industrial design.

3 A Signal Processing Approach for Freeform Feature Reuse

The fundamental idea in the signal processing-based approach for FFF reuse is that, by treating the Region of Interest (ROI) on a shape geometry as a surface signal, which can be equivalently depicted using its frequency components, the retrieval and the reusing of the FFF information content can be achieved by means of signal decomposition and synthesis, respectively. For the basic assumptions and formulations on using this approach, please refer to [6] [13] [14].

Generally, a ROI can be sampled or resampled to a relatively evenly spaced grid—the matrix representation, which can be represented by a frequency model. This model is referred to as the Fourier shape model, with the following definition.

Fourier Shape Model. Given an equivalent discrete representation of a ROI $S:\mathbf{f}(u,v)$, denoted as:

$$\mathbf{P}\{(\mathbf{f}_i(m,n)) \mid m\in[0,M-1];n\in[0,N-1]\},$$

then by using the Fourier shape descriptor, the ROI can be equivalently represented as [6]:

$$\begin{aligned}\mathrm{f}_i(u,v) &= \sum_{\tau=0}^{M-1}\sum_{\zeta=0}^{N-1}\mathrm{F}_i(\tau,\zeta)e^{j2\pi(\tau u/M+\zeta v/N)} \\ &= \sum_{\tau=0}^{M-1}\sum_{\zeta=0}^{N-1}\lambda_{\tau,\zeta}\begin{bmatrix} a^i_{\tau,\zeta}\cos(2\pi\tau u/M)\cos(2\pi\zeta v/N)+b^i_{\tau,\zeta}\sin(2\pi\tau u/M)\cos(2\pi\zeta v/N)+ \\ c^i_{\tau,\zeta}\cos(2\pi\tau u/M)\sin(2\pi\zeta v/N)+d^i_{\tau,\zeta}\sin(2\pi\tau u/M)\sin(2\pi\zeta v/N)\end{bmatrix}\end{aligned}, \quad (1)$$

where $\lambda_{\tau,\zeta}=\begin{cases}\frac{1}{4} & \text{for } \tau=0,\zeta=0\\ \frac{1}{2} & \text{for } \tau>0,\zeta=0 \text{ or } \tau=0,\zeta>0\\ 1 & \text{for } \tau>0,\zeta>0\end{cases}$, i denotes the x, y, or z components in turn; and $\mathrm{F}_i(\tau,\zeta)$ are the coefficients of the exponential representation, which are determined by

$$\mathrm{F}_i(\tau,\zeta)=\frac{4}{MN}\sum_{m=-M/2}^{M/2}\sum_{n=-N/2}^{N/2}\mathrm{f}_i(m,n)e^{-j2\pi(\tau m/M+\zeta n/N)} \quad (2)$$

where $\mathbf{F}=\{\mathrm{F}_i\}$, i denotes the x, y, or z components, respectively; and the coefficients of the sinusoidal representation are determined by

$$\left.\begin{aligned} a^i_{\tau,\zeta} &= \frac{4}{MN}\iint_\Omega \mathrm{f}_i(u,v)\cos(2\pi\tau u/M)\cos(2\pi\zeta v/N)dudv \\ b^i_{\tau,\zeta} &= \frac{4}{MN}\iint_\Omega \mathrm{f}_i(u,v)\sin(2\pi\tau u/M)\cos(2\pi\zeta v/N)dudv \\ c^i_{\tau,\zeta} &= \frac{4}{MN}\iint_\Omega \mathrm{f}_i(u,v)\cos(2\pi\tau u/M)\sin(2\pi\zeta v/N)dudv \\ d^i_{\tau,\zeta} &= \frac{4}{MN}\iint_\Omega \mathrm{f}_i(u,v)\sin(2\pi\tau u/M)\sin(2\pi\zeta v/N)dudv \end{aligned}\right\} \begin{pmatrix}\tau=0,1,2,\cdots,M-1;\\ \zeta=0,1,2,\cdots,N-1.\end{pmatrix} \quad (3)$$

where the integral area Ω is defined by

$$\Omega=(-M/2\le u\le M/2;-N/2\le v\le N/2).$$

Equation (2) is called the 3D *Fourier Shape Model* (FSM) of $\mathbf{P}$. And the position information of the shape of the ROI is kept by

$$\left(\mathrm{F}_x(0,0),\mathrm{F}_y(0,0),\mathrm{F}_z(0,0)\right)$$

in the special domain.

The FSM is, in fact, a representation of the ROI in terms of its frequency components. With this formulation, in the frequency domain, the FFF retrieval and reuse can now be formulated as below.

3.1 Freeform Feature Retrieval

In the scope of shape modeling, the term *freeform* often employed to denote a surface with the continuous curvature variations. FFFs are often thought of as such geometric elements that have distinct shape characters in contrast to the base surfaces. In other words, the feature is composed of the relatively higher frequencies, whereas the base surfaces the lower frequencies [15] [6]. Therefore, the retrieval of the feature content can be achieved by a filtering operation, as below.

$$\mathbf{F}_f=\mathbf{F}*G_f, \quad (5)$$

where $\mathbf{F}_f$ is the FSM of the feature; $*$ denotes a digital convolution; and G_f the high-pass filter. For a detailed discussion, please refer to [6].

3.2 Freeform Feature Reuse

In the proposed approach, the reuse of a FFF is implemented by a controlled signal synthesis, as:

$$\mathbf{F}=\mathbf{F}_t+\mathrm{h}\,\mathbf{K}_c\mathbf{F}^s_f, \quad (6)$$

where $\mathbf{F}_t$ denotes the FSM of the target shape; h is a filtering function that operates on the spectral components of the FSM of the FFF; $\mathbf{K}_c$ is a constant

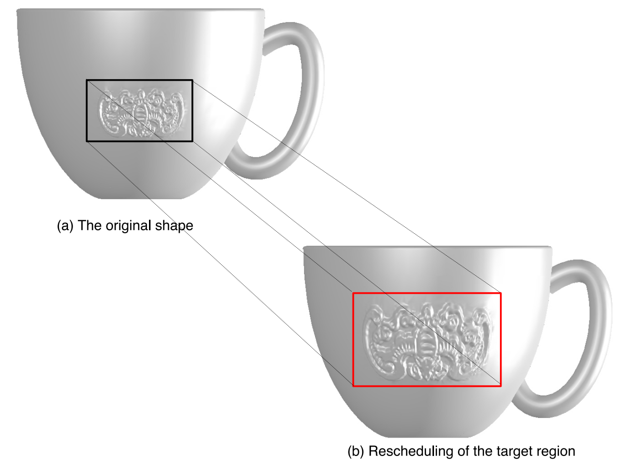

Figure 1. An example of feature scaling.

vectorial matrix control-ling the direction of the displacement mapping; and $\mathbf{F}_f^s$ is the FSM of the FFF, and the position information in the its FSM is eliminated, i.e., $\mathrm{F}_i(0,0)=0$ (i denotes x, y, and z components, respectively).

The reused FFF is incorporated into the target model by means of a displacement mapping with several mapping effects. For a detailed discussion on the implementation of the displacement mapping, please refer to [16].

This proposed approach could facilitate shape modeling in industrial design in many ways; for instance, it enables the abstraction of regional shape information; provides support for fast shape creation and alternation; bridges the gap between traditional design means and advanced CAD tools, as demonstrated below.

4 Shape Abstraction and Regional Shape Manipulation

As described above, the FSM of a regional shape can serve as an operator to implement the transition from the spatial to the frequency domain. According to the principle of shape representation in the frequency domain, techniques for the abstraction of shape information and for shape manipulation can be developed as follows.

4.1 Regional Shape information Abstraction

By propagating the signal decomposition methods, a ROI can thus be represented as

$$\mathbf{F}=\mathbf{F}_b+\mathbf{F}_f \qquad (7)$$

where $\mathbf{F}_b$ denotes the FSM of the base signal; and $\mathbf{F}_f$ the FSM of the feature signal [6].

Equation (7) defines a general scheme of shape abstraction, which can be implemented by applying the feature retrieval operators. It states that the surface signal of a shape (or a ROI) can be, in general, separated into two parts, i.e., the base surface signal, and the signal of the FFF. This provides a clue for shape manipulation at an abstract level. Hence, further processing of the given shape can be carry out by applying dedicated filters on each part of the FSMs, respectively.

Generally, the shape character of a ROI is often addressed by the FFF it carries, which is the second item in Equation (7). This abstraction scheme relates the FFF to the higher frequency components,

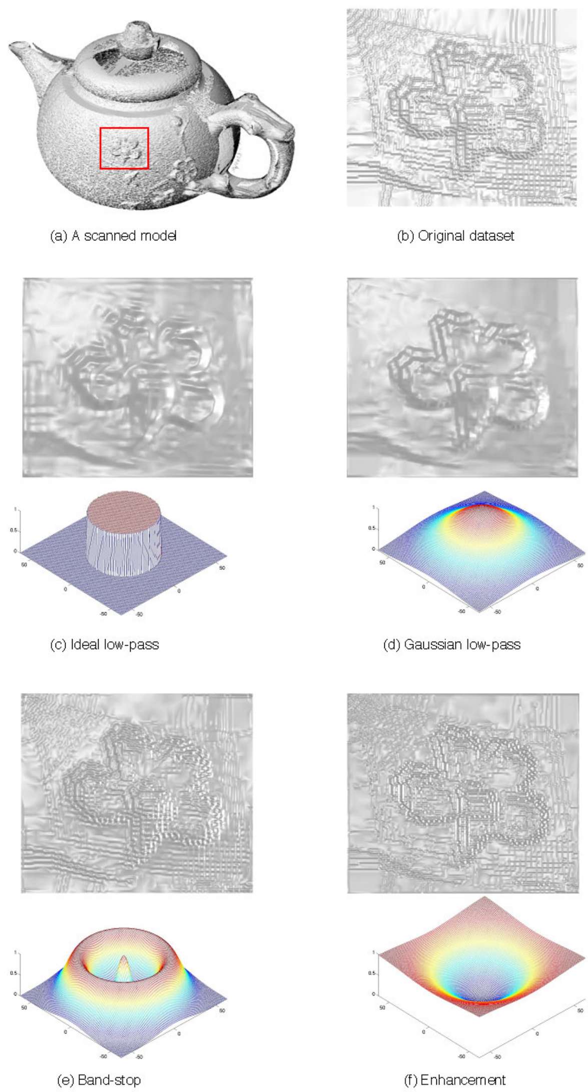

Figure 2 Examples of the shape processing effects. (a) a scanned model; (b) the selected region of interest; (c)-(f) shape processing results with different filters.

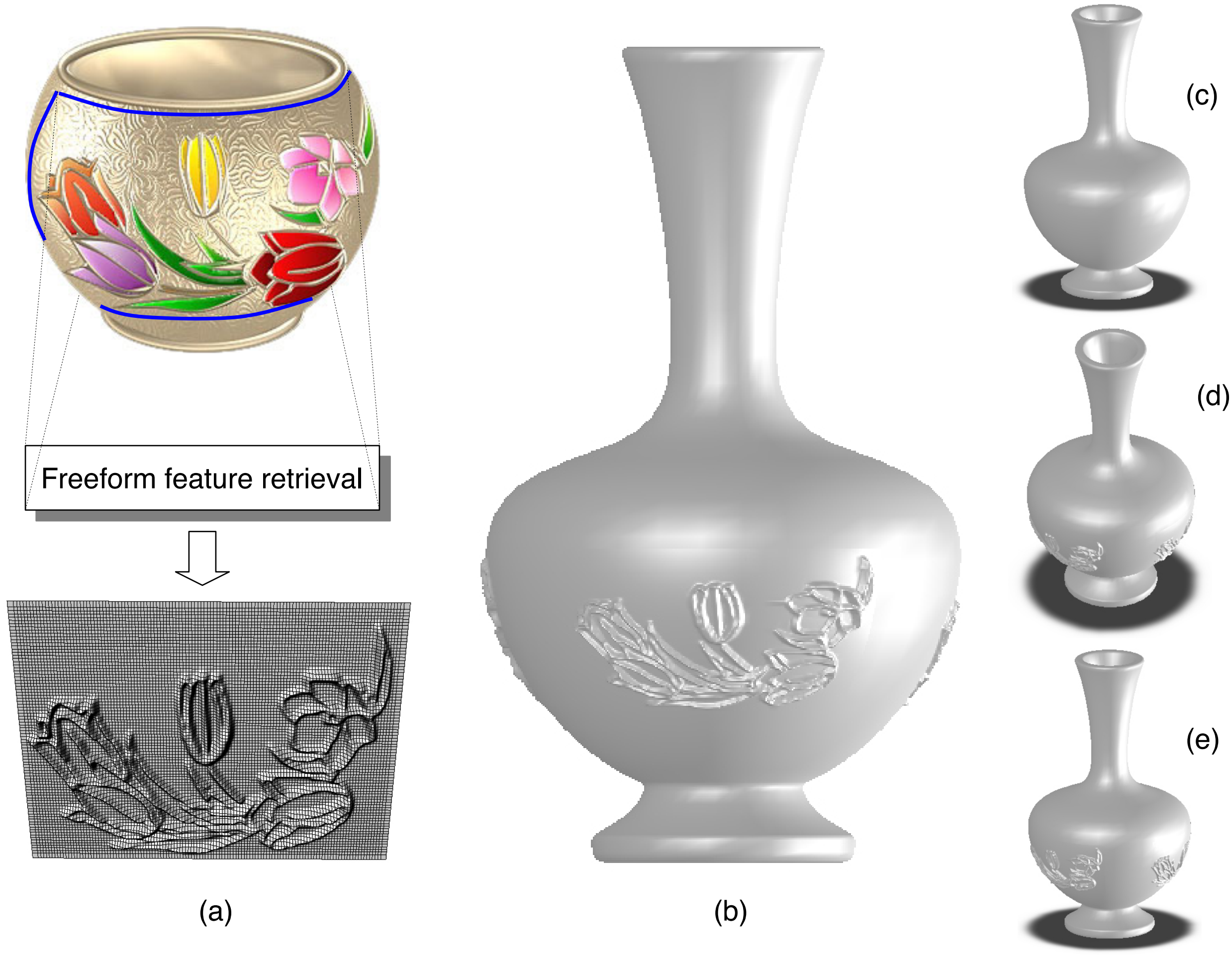

Figure 3 An example of local enrichment using the FFF reuse tool. (a) a schematic process of FFF retrieval; (b) the model with regional enriching; (c) the original model; (d) and (e) other views of (b).

whereas the base surface to the lower frequency components. Equation (7) enables us to selectively manipulating the shape character by operating on specific frequency components. For instance, we can boost the detail of a shape by amplifying its high frequency components, or depress it by reducing the intensity, which make the surface smoother.

Frequency operators have been intensively studied in signal processing, resulting in a numerous of precious operants [17] [18] [10]. The shape abstraction scheme introduced above exploits these mature algorithms to facilitate shape modeling, as demonstrated below.

4.2 Regional Shape Manipulation Using Spectral Operators

Once a regional shape was abstracted by applying Equation (7), its manipulation could be conducted by using dedicated filtering operations on the selected spectral components. The most convenient tool to be used to manipulate the FSM of both the base and the feature signal is the spectral operators or filters, which are commonly implemented by a digital convolution. For instance, to manipulate a shape that has been properly abstracted, Equation (6) can be applied.

Figure 1 shows an example of scaling the feature in an ROI. In this case, the filter h in Equation (6) is set as a constant.

It is also possible to selectively manipulate the frequency components of a regional shape. One of the examples of this kind of application is shape processing, as shown in Figure 2, in which the showing filters are utilized as shape manipulators to control the resulting shape using only a few parameters.

5 Enriching Regional Appearance

The proposed techniques provide basic facilities to support FFF reuse, which can be applied for the purpose of enriching regional appearances. It is known that one of the functions of a FFF in a shape model is to add characters, which are, sometimes,

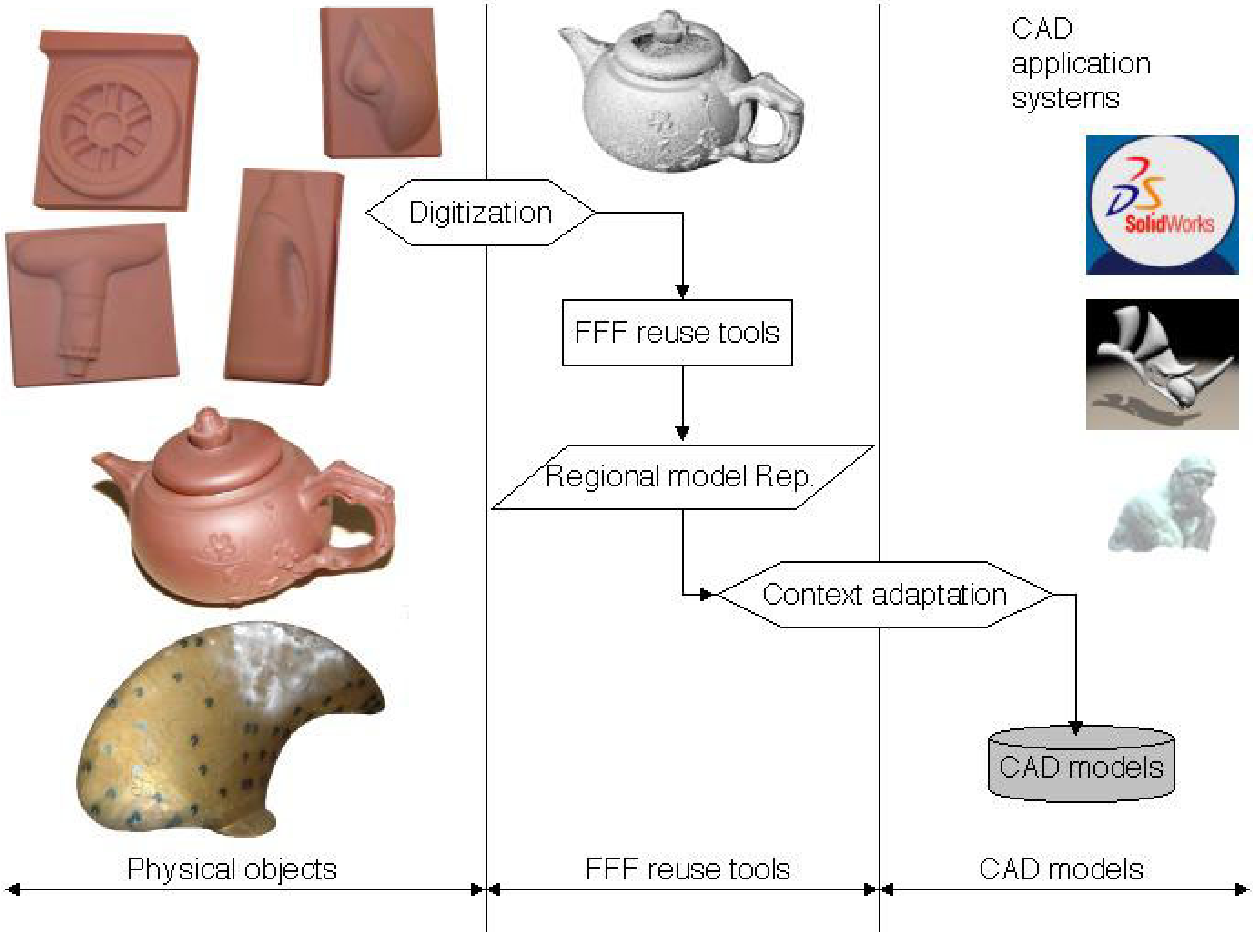

Figure 4 The signal processing-based tools for freeform feature reuse as a link bridging the physical and the CAD world.

referred to as local shape enrichment. We often call a beautifully designed product shape as stylish. However, the composition of a stylish product shape is a rather sophisticated process, in which many factors can be involved. For instance, it has been found that the topological structure variation of feature geometry can affect the design style distinctly, whereas the local feature geometry can enhance the regional characteristic appearance of a style [20].

In the context of shape modeling, the addressing of a shape characteristic can be implemented by modifying the underlying geometry or by adding feature geometries on it. Unlike surface decoration by applying patterns, colors or textures on the model surface, which virtually addresses the local appearance rather than a real perturbation of the underlying geometry, applying our proposed methods will really modify the surface geometry of a model.

Figure 3 schematically shows the regional enriching process and a comparison of the resulting shape with the original shape. The enriched model appears more vivid and characterized.

6 Bridging the Gap between Traditional Design Means and Advanced CAD Systems

Traditionally, many designers are used to start their design from a hand sketching. In order to validate the mental model, sometimes they use other rapid prototyping means, such as clay modeling, which is typically time consuming. In such circumstances, the reuse of some patterns or forms built in a previous design is rather difficult to achieve. To facilitate design reuse, new methods have been developed; for instance, in RE, an existing physical model can be computerized by digitizing and visualized on the screen. However, how to reuse these digital models partially or as whole into an existing modeling framework in a CAD system still remains challenging.

The present research has a focused attention on capturing and reusing FFFs, and is capable to bridge the gap between physical modeling and advanced

CAD systems in such a way:

- First, we acquire any digitized models as point clouds or mesh models, which can simply be read into our system. A model representation can be established accordingly;
- Secondly, the ROI in a model will be captured and interpreted into a unified representation, namely, the FSM;
- Then, some dedicated filtering tools will be applied to retrieve the information content of the feature in the ROI, which is believed to be the shape character of the ROI; and
- Finally, the retrieved feature will be merged into a CAD model by a post processing process, which actually implements a signal synthesis. The resulting model format is compliant to that in the most popular CAD application systems; for instance, it can be a point cloud model, a mesh model, or a surface model.

By this process, a FFF in a physical model will be transplant to an existing digital CAD model. Figure 4 schematically shows the functions of the proposed techniques, as a bridge between the physical objects and the CAD models. In this process, techniques for FFF reuse play an important role [6].

7 Facilitating Fast Shape Creation and Manipulation

One of the applications of the proposed techniques is to facilitate fast shape creation and manipulation. Although this might have been partially stated in other part of our research publications, here, we will give a complete description on the related issues.

In product shape modeling, FFFs have irreplaceable advantages over other entities in addressing local characteristics of a shape. However, the creation of a feature turns out to be very time-consuming due to its complexity. For instance, a regional feature, like a dragon shape, may contain hundreds of control points and topological information.

With the development of CAD technology, hundreds of existing models, either digitally or pictorially, maybe collect for reference or reuse during a modeling process. Once an interesting component was found, it is desirable to enable the designer to copy that component and to immediately implement it in the working model. As one of the amazing functions of the present techniques for FFF reuse, this can be supported by a copy-and-paste

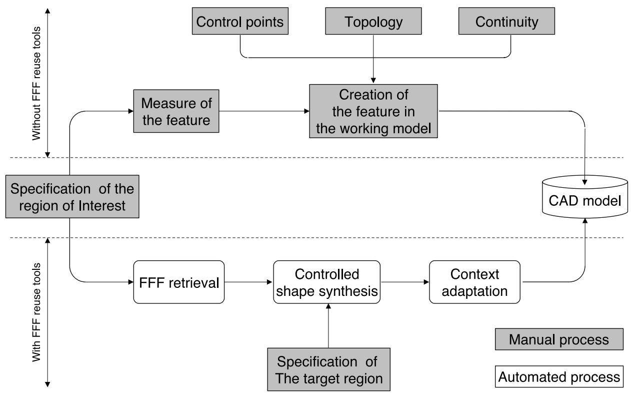

Figure 5 A comparison of the shape creation processes with or without the support of FFF reuse tools.

operation. In our approach, supporting fast shape creation was implemented by the following process:

- First, identifying and specifying the ROI, where a FFF often located;
- Secondly, capturing the shape characteristic by executing a retrieval process;
- Then schedule a target region on the working model, where the captured shape feature will be pasted. This, in fact, implements a signal synthesis operation; and
- Finally, incorporating the synthesized shape into the existing model. This achieves the inclusion of a shape feature into a target model.

In practice, the reuse of FFFs supported by applying the proposed techniques can lead to a dramatic time saving, providing high modeling efficiency. Figure 5 shows the comparison of the modeling processes of a shape feature with or without the support of FFF reuse. It appears that by using the signal processing-based tools the process of shape modeling is more automated.

8 Conclusion

This paper has introduced signal processing-based techniques for FFF reuse in shape modeling, and their applications in industrial design. Using signals to depict shape information content and to conduct information retrieving reveals a new research direction, which blends computer graphics and signal processing techniques, revealing an innovative application field. The given discussions have shown that the proposed approaches are promising. And the accompanying examples have demonstrated that applying signal processing techniques in facilitating shape modeling are effective and the efficient.

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