Design Reuse in Product Shape Modeling: Global and Local Shape Reuse

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Abstract: - Design reuse widely exists throughout in design process in the form of providing competitive product strategies, alternating design concepts, and rationalizing design implementations. In the context of industrial design, product shape model is the kernel for associating various functions and engineering properties. Product shape reuse is of great importance in promoting productivity and efficiency, maximizing the use of concentration of engineering creativity and expertise, by means of reusing successful past designs in part or in whole for new designs. Although there are diverse strategies proposed for the supporting of design reuse at the strategic level, studies on shape reuse remain somewhat inadequate, especially for the reuse of shape geometry. As a consequence, there is seldom reuse support provided by commercial CAD systems. This paper investigates issues in supporting shape reuse. Two approaches regarding product shape reuse will be proposed, namely global and local shape reuse. The former employs a coding system to encode product shape information as a whole, while the latter uses shape descriptors to depict regional shape characters. Strategies and processes for implementing these two approaches are presented. Supplementary examples will demonstrate the effectiveness of the proposed approaches.

Key-Words: - Product design, design reuse, shape reuse, shape encoding, freeform feature, shape indexing.

1 Introduction

Design reuse is the inclusion of intellectual assets built in previous designs in the creation of new designs. As in electronics and software engineering, where significant advantages are brought in by the reuse of standard or object-oriented modules [1], in the context of industrial design, design reuse is also beneficial in promoting productivity and efficiency, maximizing the use of the concentration of engineering creativity and expertise, by means of reusing successful past designs in part or in whole for new designs [2]. This makes the designing and building of a new product cheaper and faster, since the reused components are not only already available, but also tested for reliability and manufacturability. In recent years, the increasing expectation for industrial products with higher quality and lower costs has heightened the needs for computational tools being able to enforce design reuse in computer-aided product design systems.

Historically, studies on design reuse can be classified into three levels: firstly, at the philosophical level, principles and methodologies of reuse are developed [3] [4] [5] [6]; secondly, at the knowledge level, product design, process plan, material choice, heat-treatment, and other engineering related assets are investigated [7] [8]; and finally, at the information level, geometric shape related properties and data of products are explored, such as geometric model of artifacts or components, shape style expressed by topological elements, and freeform features represented by local geometric parameters [9] [10] [11].

Although having been studied for ages, design reuse at each of those three levels still remains challenging. For instance, due to technological limitations in existing CAD/CAID systems, design knowledge is often poorly captured, archived and managed [12]. Furthermore, at the information level of design reuse, because of lacking for mechanisms of sufficient abstract, there is often nearly absent of high-level shape parameters in a geometric model that are able to serve as reusable knowledge. As a consequence, model editing is restricted to operations such as local and global geometric deformations, primitive adding, or removing. The modification of a feature parameter, which in some cases is the most natural operation [13], is commonly not supported. For instance, reuse of geometric objects is presently possible only in some very specific situations, namely either as a hard copy-and-paste operation of regional surfaces, or via Boolean operations when the geometric object is relatively simple, such as that for prismatic and analytical geometries [10]. However, it is also known that, for more complex geometric objects, there is a strong need for reuse support [14].

In this paper, we investigate strategies for design reuse at the information level, namely, shape reuse. The remaining part of this paper is organized as follows. In Section 2, an overview of the strategies for shape reuse will be presented; Approach for global shape reuse will be discussed in Section 3; And Section 4 discusses the strategy for local shape reuse; In Section 5, some examples are provided for the evaluation of the proposed approaches; Finally, conclusions and clues for future work will be given.

2 Overview of the Strategies for Shape Reuse

With the pervasive application of CAD tools and digital acquisition equipments, during the past decades a tremendous amount of design knowledge has been accumulated via diverse repositories of product models over the Internet or within organizations. The exploitation of these valuable resources, especially that of product shape models, has been becoming an attractive, as well as challenging research field to the design research community, for its merits leading to time and money saving, and avoiding unnecessary mistakes [15] [12] [16]. This demand directly motivates the study of shape reuse.

In fact, shape reuse is one of the greatest interests in *Reverse Engineering* (RE) as well [17], especially, when the geometric model of a product is reverse-engineered [18]. Shape reuse can be very helpful from a designer point of view, since it facilitates fast shape creation and modification. Benefits of those kinds of supporting tools have been intensively investigated, for instance, in the fast shape design project [19] [20], or cut-and-paste operations in local enrichment [21] [10] [22].

Practically, the study of reuse of shape information usually follows two strategies: either by treating the product model as a whole by using techniques such as *Group Technology* (GT) [23], or as feature compositions [9] [24] [11]. The former addresses the global properties of the product shape, for instance, by means of the Opitz coding scheme [25] [26], design knowledge is represented according to the abstract of form shapes, and supplementary properties, such as tolerances, materials, production operation types, sequences, and functions chosen by the manufacturer [23] [27], while the latter investigates the local properties, such as the parameters of a piecewise geometry, a Freeform Feature (FFF), or the Region of Interest (ROI).

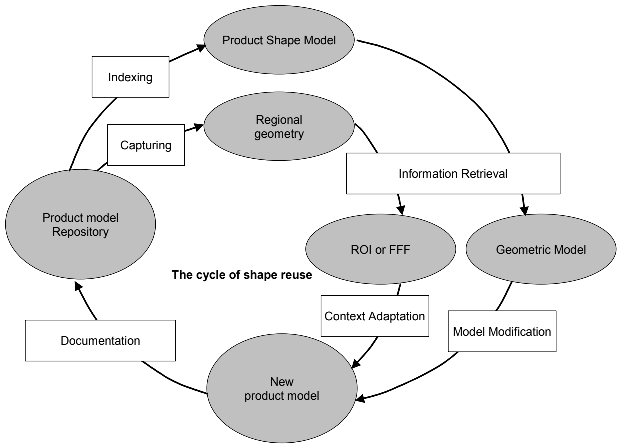

Fig. 1 Overview of strategies for shape reuse.

Critical issues in shape reuse are typically addressed by the following aspects: (i) capturing of the parameters of shape geometry or indexing of the model shape information; (ii) retrieval of shape parameters or geometric model; (iii) adapting the retrieved shape parameters to fit with the existing modeling context, or conducting direct modification on the retrieved model; and (iv) documentation of the current product, which in turn can serve as the input for reuse in the future. The cycle of shape reuse is schematically shown in Figure 1, which is composed of two approaches, namely, global and local shape reuse.

We have investigated these approaches, and their implementation will be presented in the following sections, respectively.

3 Global Shape Reuse

Global shape reuse is a highly abstract method

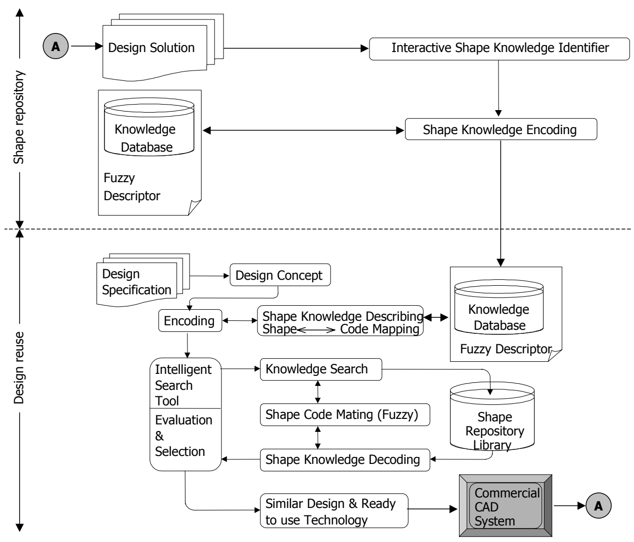

Fig. 2 The process of global shape reuse.

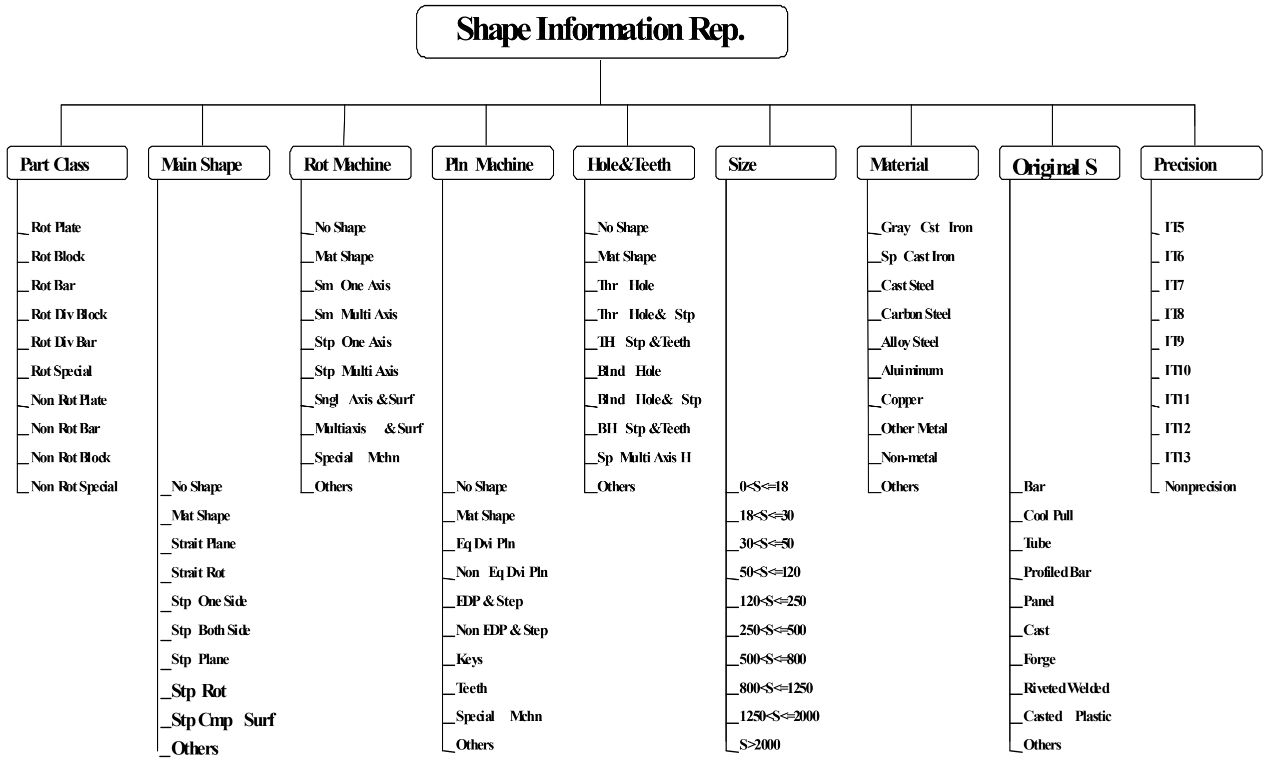

Fig. 3 The dictionary for the abstracting of global shape information.

generally implemented by abstracting the shape information to a higher level. For instance, in a coding system, the code of the shape information for a part are often sketched out by a multi-component vector, in which each component stands for a specified shape class. These kinds of methods take great advantages from the philosophy of *GT,* incorporating with such techniques as part shape classification, encoding, or part shape information retrieving. The complete process for global shape reuse is shown in Figure 2.

Global shape information acquisition. Several shape characters have been identified in this regard, which are suitable for categorizing part shape information, such as part class, main shape, rotational machining, plane surface machining, additional holes, teeth and forming, and supplementary part attributes. The supplementary part attributes include some auxiliary features such as dimensions, material, original shape of raw material and accuracy. In this approach, the acquisition of shape information closely relies on human intervention.

Shape information representation. Numerous techniques regarding the representation of shape information have been investigated during the past decades, ranked from geometric feature representation, functional representation, to commitment transition [31]. Researchers have proposed several ways to represent part shape information, such as a 14-digit GT based representation, standardization based classification code, and expert knowledge based representation method [28] [29] [30]. Although these methods can work under different circumstances, problems remains being lacking of simplicity, as well as integrity.

In our implementation, we adopt the 9-digit GT coding scheme. The product shape information is abstracted to a shape code $C \in \mathrm{I}^n$, which is defined by

$$C = \{c_i \mid i = 1,2,\cdots,9.\} \qquad (1)$$

where $1 \le c_i \le 9$. The n -tuple vector C is also called a generalized GT code. The dictionary used for the abstracting of global shape information is shown in Figure 3 [11].

Global shape reuse: The process of shape reuse can be simply depicted as: at first, documenting the part shape information generated by a mechanical CAD system by utilizing an interactive shape encoding tool; then achieving the shape information code and setting up internal link between the codes and part models. When starting a new design, supposing the designer is able to specify (or estimate) the conceptual shape, hence a schematic shape code can be obtained by applying the encoding process, say, $D \in \mathrm{I}^n$. Undetermined bits in D are set to zero. Then a search can be made within the repository with the following criteria, either $C = D$ or $|C - D| < \varepsilon$, where C is the index of a candidate shape model in the repository, and

$$|C - D| = \sum_{1 \le i \le n} |c_i - d_i| \qquad (2)$$

denotes the measure of differences between C and D. ε is an nonnegative valve value, which is specified by the user. In most cases, the searching of a candidate model is based on a Fuzzy mode, controlled by the valve value ε. For instance, $\varepsilon = 0$ may result in an exact search, whereas $\varepsilon = 9 \times (9 - 0) = 81$ may cause the system bringing in the entire set of models in the repository.

We have implemented several tools for indexing and reusing of global shape information incorporating within a CAD system. Advantages of this approach include: (i) it provides a basic mechanism to depict and deposit shape information at the abstract level; (ii) it helps to partially automate shape conceptualization process by providing diverse candidates of similar design, thus adding intelligence to a CAD system; (iii) Growing along with design experience, the system may evolve itself by aggregating more and more part shape information, therefore it will become more and more intelligent and powerful.

However, because of both geometrical and topological complexity of a part shape, it is difficult for the application system to acquire shape information automatically from an existing design. So, for part shape recognition, an interactive method has been adopted [24]. In addition, the main drawback of this approach remains that it does not provide mechanisms to support regional shape indexing or reuse. To solve this problem, techniques for local shape reuse have to be invoked.

4 Local Shape Reuse

In local shape reuse, the product shape model is considered as a composition of a set of form features, similar to the conventions in a commercial CAD system. Noticeably, FFFs have been long recognized as the pivot elements in product shape modeling. As sophisticated high-level geometric entities, FFFs are able to provide the advantageous mechanism for treating sets of elements as single entities [32] [33], thus enabling fast creation and modification of the shape geometry [34]. The reuse of FFF is typically of great interest in design community for its benefits in facilitating fast shape creation.

Our supporting tools for local shape reuse are implemented by using signal-processing techniques, which take the following process. First, the form surface in the ROI of an existing shape model are sampled; Secondly, by using the Discrete Fourier Transform (DFT) the sampled data will be transformed into a series of spectral components in the frequency domain; Thirdly, the feature extraction can be implemented either by decomposition algorithms or by applying frequency-based operators, such as dedicated filters; Fourthly, reuse of the feature is carried out by linear summation of the feature spectrum and the spectrum of the target surface; Then, the modified Fourier Transform (FT) of the ROI will be transformed back to the spatial domain by using reverse DFT. And finally, a reconstruction process will rebuild the resulting shape. The FT of FFFs can be stored in a repository, so that the designer is able to search for candidate FFF by providing a vague description of the schematic shape character. Pivot issues in local shape reuse consist of the following aspects: (i) regional shape representation; (ii) FFF retrieval; (iii) indexing of FFF shape information; as well as (iv) shape synthesis. The complete process for FFF reuse is shown in Figure 4.

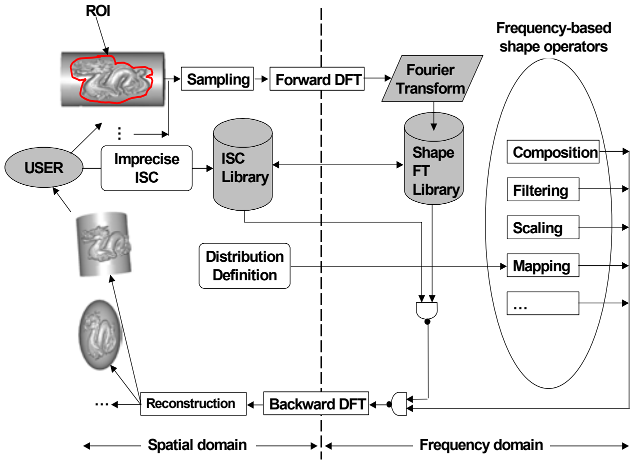

Fig.4 The process of freeform feature reuse.

Regional shape representation. A regional surface can be thought as a 2D surface signal, which

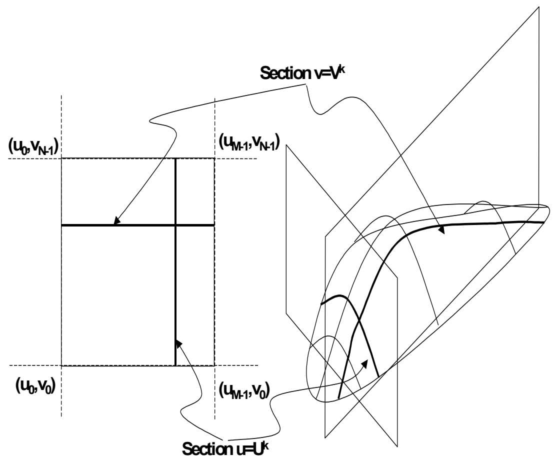

Fig. 5 A schematic view of regional surface discretization.

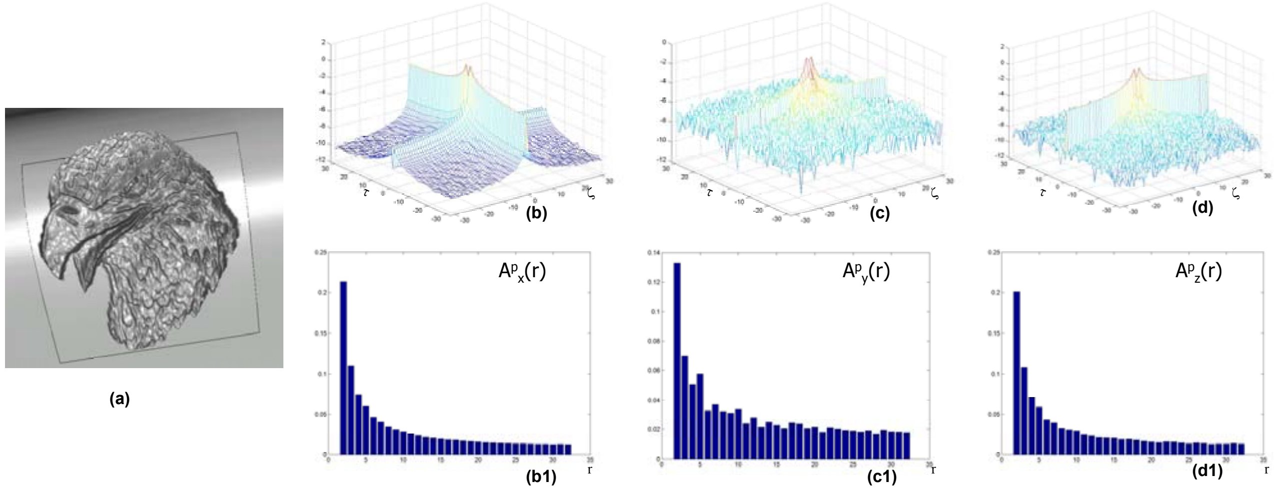

Fig.6 An example of the indexing of shape information of a freeform feature. (a) a feature in the region of interest; (b) (b1) x-components; (c) (c1) y-components; and (d) (d1) z-components.

can be equivalently represented as a discrete distribution. For a $[0, M-1]\times[0, N-1]$ regular sampling grid on a regional surface S, we can obtain

$$S = \{s(u_m, v_n \mid 0 \le m \le M-1, 0 \le n \le N-1\}$$

on a ROI as shown in Figure 5. The FT of the ROI can be computed by means of DFT as:

$$S = \Im^{-1}\{f(\tau,\zeta) | \tau \in 0,1,\cdots,M-1, \zeta \in 0,1,\cdots,N-1\} \quad (3)$$

where $\Im^{-1}(\cdot)$ denotes inverse DFT, and $f(\tau,\zeta)$ are the frequency components defined by

$$f = f(\tau,\zeta) = \frac{1}{MN}\sum_{u=0}^{M-1}\sum_{v=0}^{N-1} s(u_m, v_n) e^{-j2\pi\left(u\tau/M + v\zeta/N\right)} \quad (4)$$

where $s(u_m, v_n)$ are the elements of the sampling matrix. And f is called the 3D Fourier model of shape S.

To make the sample data periodic, a possible way is to expend the data sample in S by tracing back from one side of the surface to the other side. This makes a piece of open surface virtually closed [36].

Sampling precision can either be controlled by Nyquist rate (precise sampling) or by the designer (approximate sample). Detailed discussions on sampling issues please refer to [22] [35].

FFF retrieval. Psychological study suggests features are typically composed of relatively higher frequency components depicting the variation of fine details, whereas low-frequency components forms the base shape [38]. Although low or high frequency is a relative concept, a dedicated high-pass filtering can be employed to filter out low-frequency components, which is thought of as the signal of the base shape:

$$f_s = (1-H)f \quad (5)$$

where f_s is the FT of the feature shape, f denotes the FT of the ROI, and H a low-pass filter. In case a base surface representation is available, (for instance, in a surface or solid modeling system the base surface is always kept after feature interaction.), exact feature retrieval can be done by simply replace Hf with the Fourier model of the base surface.

Coding of the shape information of a FFF. A *pure* feature is usually free of location information, i.e., the retrieved FFF should be represented as a height field distribution located at the $z = 0$ plane, which means $f(0,0) = 0$. Therefore, a normalized cumulative function can be defined on the Fourier model of the ROI with the following form

$$A^p(r) = \frac{\sum_{\tau=0}^{M-1}\sum_{\zeta=0}^{N-1} A(r,\tau,\zeta)|f(\tau,\zeta)|}{\sum_{\tau=0}^{M-1}\sum_{\zeta=0}^{N-1}|f(\tau,\zeta)|}, r \in 0,1,\cdots,M/2; M \le N \quad (6)$$

where $A(r,\tau,\zeta) = \begin{cases} 1 & r-0.5 \le \sqrt{(\tau - M/2)^2 + (\zeta - N/2)^2} \le r+0.5 \\ 0 & otherwise \end{cases}$,

which can serve as the identity of a FFF [37].

Obviously, $A^p(r)$ is invariant of translation, scaling, and rotation. And this definition abstracts a FFF to three numerical series, namely, x, y, and z-components, which is much compact than its original dataset. For instance, for a $M = N = 64$ sampling grid represented with $64\times64\times3$ real numbers, its index code consists of only 32×3 real numbers. Figure 6 shows an example of the encoding of geometric parameters of a FFF.

Shape reuse via synthesis. After retrieval, the FFF shape can be reused in a new design. Following the process depicted in Figure 4, supposing the FT of the ROI on the target shape is given by f_g, then the general shape reuse can be implemented by signal synthesis, defined as:

$$f_c = \sigma f_s + f_g \quad (7)$$

where f_c is the FT of the composed shape, f_s the FT of the feature shape; σ is a control function, which determines the influence of f_s on the synthesized shape. The inverse DFT of f_c will restore the resulting shape elements in the spatial domain, which can be incorporated in the existing model with or without further processing [22].

Compared with global shape reuse, reuse of local shape seems more flexible and preferable for a designer who is conducting a shape modeling, especially in local character enriching. However, the quality of the retrieved feature relies heavily on the digital filter employed. This turns out to be a negative character, which appeals further investigation.

Pure feature retrieval is the key point in the approach proposed, which usually is not or cannot be handled by other retrieving methods. Although it is known that decomposition of a compound signal is difficult, this approach can work under circumstances, for instance, when the feature is located on a relatively simple geometry or the base surface can be represented by a few low frequency components. Increasing filter sensitivity and band-pass quality can definitely improve the quality of the retrieved FFF.

5 Examples and Discussions

Global shape retrieval. In order to retrieve the information of a shape model from the shape repository, a reasonable valve value of searching should be pre-assigned. In case of an exact search, similar parts in terms of the conceptual shape will be retrieved except that the difference of size (which still remains in the same level of measure) or unspecified bits. A fuzzy search with larger valve tolerance of searching will bring the designer a broader set of parts for further choice, possibly with unexpected shapes or shape elements. Figure 7 shows the results of these two different searching strategies.

In global shape retrieval, the number of resulting shape depends on the size of the repository as well. A rich repository may give more candidates for a given criteria of vague searching. After choosing a candidate, a new design can now be sketched directly on the candidate model by means of geometric modification, which is normally supported by most of the CAD systems.

Local shape reuse. Figure 8 demonstrates the reuse of a FFF. The FT of the feature is created using feature extraction algorithms described in Section 4. The ROI on the target model has to be sampled using the same grid as the feature shape, in order to

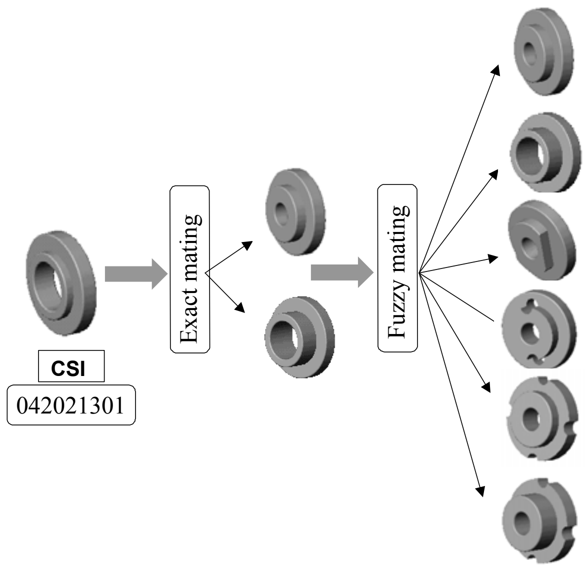

Fig. 7 An example of global shape retrieval.

implement the linear composition by Equation (7). Final models are obtained by interpolating the resulting regular grid using NURBS. And the boundary of the synthesized shape is stitched to the adjacent patch along borders with G^1 continuity, which is generally implemented by a post processing process, including reparametrization along the FFF boundary.

Since adopting the discrete representation scheme, strategy for local shape reuse can adapt to diverse modeling contexts; for instance, it can be applied in environments with such model representations as solid model, B-Rep, surface model, mesh model, and point cloud model, with minor or without preprocessing.

In addition, limitations for the proposed approach of FFF reuse are as follows. (i) Since the precision of discretization depends on the sampling rate, non-band-limited surfaces cannot be precisely represented, such as prismatic surfaces or surfaces with cracks, which contain infinite frequency

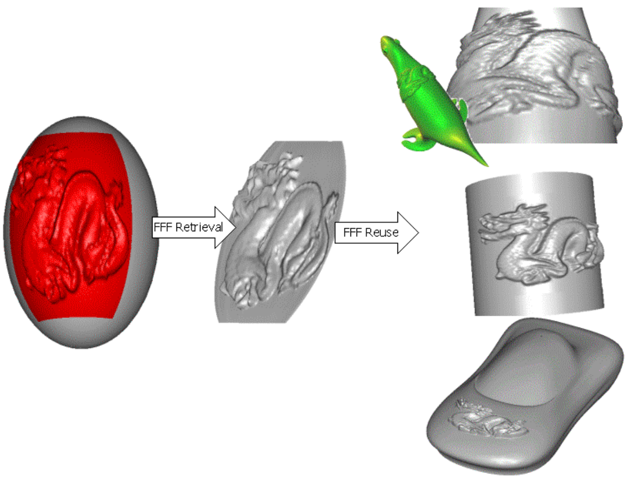

Fig. 8 Examples of FFF reuse.

components; (ii) proposed algorithm for FFF reuse cannot handle such cases as self-folding surfaces, in which the FFF to be reused may self-intersect, as what happens in a normal height field mapping.

Although with these limitations, the proposed approach for local shape reuse can still be preferable, especially during the conceptualization phase of product shape modeling, where a fast shape characterization is always the most concern rather than a fine turning.

Even though both of these approaches handle the geometric model of product shape, strategies for local and global shape reuse are not comparable. Each of them is usually employed to enforce different aspects in the process of design reuse.

6 Conclusions and Future Work

In this paper, we have presented two strategies for reuse of both global and local shape. The strategy for global shape reuse can help to speed up the shape model creation in a new design at the beginning phase by providing candidate shape models that serve as the starting point, while the strategy for local shape reuse may be employed to conceptualize regional character of a shape model in designing. In fact, as the kernel of the strategy for global shape reuse, GT has been widely accepted in diverse expert systems. It has been no doubt that the proposed global shape reuse strategy can improve the intelligence of an existing CAD system. Supplementary examples demonstrated the effectiveness of these proposed approaches.

It has been no doubt that shape reuse is an effective way to support design reuse, in terms of facilitating fast shape geometry creation and manipulation, as well as local enrichment. Although there are still some limitations on the proposed approaches, they are still preferable and applicable under certain circumstances, for instance, strategies for global shape reuse may help at the conceptualization phase when conducting a new design, whereas strategies for local shape reuse can facilitate regional modification or local shape enrichment.

Future research may concentrate on these aspects: (i) shape repository enrichment and fine turning of searching strategy for global shape reuse, as well as investigating high-level abstracting scheme for encoding of global shape information; (ii) improving the design of fast, efficient filter for implementing FFF retrieval, and developing fast computational algorithms for large dataset handling in discrete representations.

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