Reverse Engineering Based on Virtual Volume Sculpting

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ABSTRACT

This paper presents a novel reverse engineering methodology that is based on volume removing. Given a physical model, virtual clay in which the model can be embedded is generated in the computer with the help of a fixture. The virtual clay is represented by voxel arrays and the dimension of the virtual clay is defined based on the bounding box of the model. When digitizing, a three dimensional position tracker is moved around the physical model in a freehand manner by the user. The movements of the tracker are reflected by its counterpart in the computer: a virtual tracker. The swept volume of the virtual tracker will be removed from the virtual clay. When no more virtual clay can be removed, the remained part of the virtual clay is a volume representation of the physical model. The tracker used in this paper is a probe attached to a six degree of freedom (6DOF) haptic device. Physical constraints and virtual constraints are coupled in the system. The strength and weakness of the presented method are analyzed and the applicability is discussed.

Keywords: Reverse engineering; Volume representation; Volume sculpting; Haptic shape modeling.

1. INTRODUCTION

Reverse engineering (RE) starts from an existing physical object. By various digitizing methods, point cloud data of the object surface is collected automatically or manually. Point cloud data is then segmented and used to generate meshes or parameterized curves and surfaces with fitting operations. The output data is a surface representation of the physical object. This surface representation is sent to CAD system for modification and CAM system for manufacturing process planning.

In this paper, a different philosophy is introduced to reverse engineering practice, that is, a freehand volume removing method. To illustrate the concept, let's consider the case of a 2D rubbing as shown in Fig. 1 (a). We need to get a bitmap copy of the coin. One way is to get the pattern point by point / curve by curve with a pen or a digitizer. But there is an easier way to do this: placing a paper over the surface of the coin, rubbing the paper gently with a marking agent such as a pencil. When the entire area of the paper is rubbed by the pencil, a representation of the raised/indented coin surface is copied onto the paper. It can be observed that the rubbing operation is in a freehand manner. The operator doesn't need to care about the exact geometry of the surface, such as points, curves. A surface copy of the coin is shown in Fig. 1 (a) to the right.

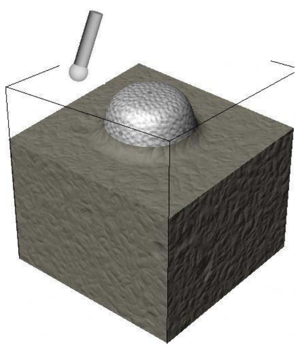
The proposed RE method is an analogy of rubbings. The surface of the physical object is not being measured or digitized. Instead, a block of virtual clay that entirely contains the physical object is generated in the computer. The marking agent here is a spatial position tracker. When digitizing, the tracker is moved along the object surface and around the object. We call this operation 3D rubbing. The tracker's movements are mapped to the virtual tracker in the computer. The swept volume of the virtual tracker is removed from the virtual clay. Fig. 1 (b) shows a physical model to be scanned. As illustrated in Fig. 1 (c), while material is being removed, the model is emerging from the virtual clay. When the entire volume of the virtual clay is swept by the virtual tracker, the remained part is a volume representation of the physical object. Triangular meshes can be obtained by "marching cube" family algorithms. The tracker used in this paper is a probe attached to a haptic device with 6DOF position/orientation sensing.

In some commercially available articulated type manual digitizing systems, e.g. MicroScribe®, the collected point cloud data, as shown in Fig. 1 (d), may contains many noise data due to the clumsy manipulation. In the proposed reverse engineering method, redundant scanning points can be avoided because the emerging model in the virtual clay can be used as a guide and provide the hint to users not to trace the already scanned surfaces. What's more, with the aid of force constraint planes provided by haptic devices, structured scanning paths can be achieved.

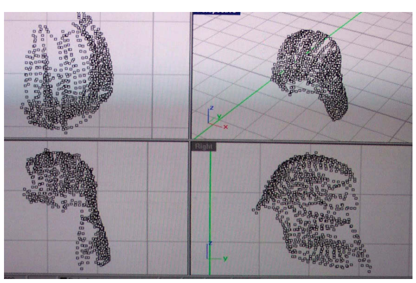
Essentially speaking, the proposed method is a volume sculpting method or subtractive modeling method. The

(a) Rubbing a coin

(b) Physical model



(c) Model emerging from virtual clay



(d) Point cloud data with noise

Fig. 1. Material removal based reverse engineering

constraints applied to the volume sculpting procedure are not those geometrical or physical modeling constraints, but the surface of the physical object. The immediate output of this method is a volume representation. The proposed method features point cloud free and freehand digitizing. The former eliminates the computation on point cloud data segmentation and curve/surface fitting operations. The latter alleviates laborious digitizing operation in manually contact measurement. The introduction of haptic device to digitizing operation makes the whole clay removal process more realistic. The coupling of the virtual constraints generated by haptic device and physical constrains caused by the concerned object provides an intuitive human-machine interactive environment which speeds up the procedure of digitization.

The remaining part of this paper is arranged as following: Literature review on the key techniques used is given in section 2. Section 3 presents the proposed methodology. Sculptured object digitizing examples are illustrated in Section 4. The pros and cons of the proposed RE method are discussed in Section 5.

2. LITERATURE REVIEW

Two categories of techniques are employed in the proposed RE method: reverse engineering and volume sculpting. Related works on these techniques are reviewed briefly.

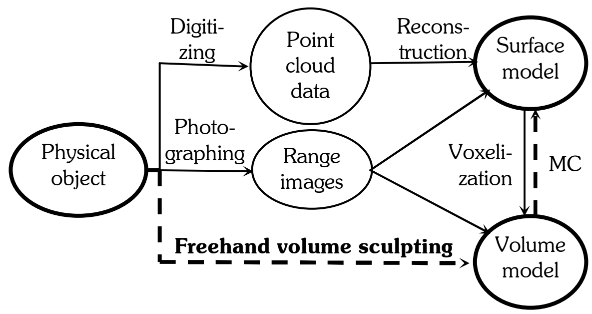


Fig. 2. Reverse engineering – from physical object to CAD model

2.1 Reverse Engineering

The process of generating a computerized representation of an existing part is known as reverse engineering. Unlike the traditional manufacturing philosophy of designs being transposed into products, reverse engineering measures, analyses, modifies, and produces the products based on existing artifacts [1]. Using 3D data collected by a digitizer, a CAD model can be created and employed in many subsequent manufacturing processes. An in-depth review of reverse engineering is discussed in a paper by Varady *et al.* [2]. A concise flowchart of conventional RE and the proposed RE method shown as dashed line is given in Fig. 2. The input of RE processes is the physical object of interest, while the output is its CAD model, either surface representation or volume representation. The exchange between surface and volume model can be done by mature algorithms such as voxelization and marching cube (MC) algorithms. Surface representations and fitting methods for reverse engineering are summarized in [3]. In conventional RE processes, 1D (point cloud data) or 2D (range images) sampling data of the surface of interest is acquired by digitizing devices (CMM, laser scanner, etc.) or photographing devices (CCD camera, ICT, MRI, *etc*.). The dashed arrows in Fig. 2 indicate the authors' method: a 3D position tracker is used as a volume removing tool. 3D volume data is obtained directly without lower dimensional data collection.

RE methods diverges from data measuring strategies. Commonly used data acquiring devices can be categorized into contact or non-contact devices. Contact type devices are generally more accurate but slow in data acquisition, and vice versa for non-contact type devices. According to whether the probe is held by operators, contact devices can be further divided into two classes: automatic devices and manually holding devices. A typical example of automatic devices is CMM. Digitizing accuracy as high as ±0.5 μm can be achieved with CMM digitizing. A typical manual contact digitizing device is MicroScribe® provided by Immersion®. Its accuracy is about 0.3 mm. The digitizing processes of contact devices are clumsy. The output of this type of devices is always point cloud data. The major drawback of contact devices is that they may deform or even damage the surface of the object being digitized because of the direct physical contact. Non-contact devices measure the point coordinates using distance measuring methods, such as laser scanner, sonar. The merits of non-contact methods are high scanning speed and accuracy. The accuracy of laser scanning can be as high as ±5 μm. But it is difficult to adjust the beam path or too expensive for some practical applications. What's more, the accuracy will be decreased when the surface reflectance varies, the light paths to the sensor are partially occluded, or the material is transparent or semitransparent.

When the point cloud data is available, reconstruction algorithms are used to establish the CAD model. A survey on the reconstruction algorithms is reported by Petitjean [4]. He generalized the reconstruction process as four consequential tasks: local geometry estimation, noise data removing, segmentation, and surface fitting.

The RE methods reported in the literatures has a common point: the intermediate data representation is points. In contrast to these methods, the one presented in this paper is based on freehand volume sculpting technique. The intermediate data is a volume structure.

2.2 Volume Sculpting

Volume graphics is concerned with the modeling, processing, and visualization of voxels. The process of discretizing a geometrically represented 3D object into a voxel model is called voxelization. Kaufman [5] proposes that graphics is ready to make a paradigm shift from 2D raster graphics to 3D volume graphics with implications similar to those of the shift from vector to raster graphics. Volume representation can be regarded as the ultimate representation method because it is much more close to the nature structure of physical object: atom-molecule structure. The limitation of volume representation is the trade-off between accuracy and efficiency because the approximation accuracy is determined by the discrete resolution. Volume graphics, voxelization and volume rendering have attracted considerable research in recent years.

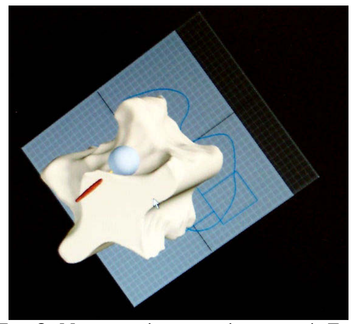


Fig. 3. Haptic volume sculpting with FreeForm®

Volume modeling techniques are known for their robustness and flexibility. However, the interaction with volume data imposes great challenge to computer science. Galyean and Hughes generalized the 2D painting metaphor to volume sculpting by extending the 2D canvas to 3D volumetric clay [6]. Wang and Kaufman proposed a modeling technique based on the metaphor of interactively sculpting complex 3D objects from a solid material block [7]. They developed a localized ray-casting algorithm to achieve real-time interaction. They argued that 2D input device is easier to use than a 3D one if collision detection is not implemented. Baerentzen proposed a volume sculpting method based on octree representation [8]. Schmitt *et al*. developed a technique for interactive volume sculpting using parametrically defined free-form volumes, *i.e.* B-Spline volumes [9]. They modeled volume sculpting as a combination of global and local deformations. They used parametrically defined volumes with functional clipping to define global deformations. For local deformations, they use real time carving. Ferley *et al*. presented a sculpture metaphor for rapid shape-prototyping [10]. The sculpted shape is the isosurface of a spatially sampled scalar field. The user can move the scene and/or the tool with a Spacemouse (6D input device), or a 2D mouse using virtual trackball. Pyo *et al*. proposed a volume-carving algorithm that uses the shear-warp factorization of the viewing transform to carve out a part of the volume data [11]. The idea of multi-dexel volumes as a volume representation is suggested by Müller *et al*.

[12]. They use that representation to overcome the difficulty of unequal sampling densities dependent on the slope of the surface relative to the direction of the dexels. Corresponding sculpting algorithms are presented and employed to simulate the milling processes in mechanical engineering.

The volume sculpting methodologies mentioned above are all based on visual interaction only. The inherent shortcoming of using 2D images to represent 3D object makes the visual-only interaction non-intuitive and inefficient. With the emergence of force feedback devices, haptic cue is added to the interaction of volume sculpting. A haptic modeling system has the advantages of allowing the user to touch, feel, manipulate, and model objects in a 3D environment

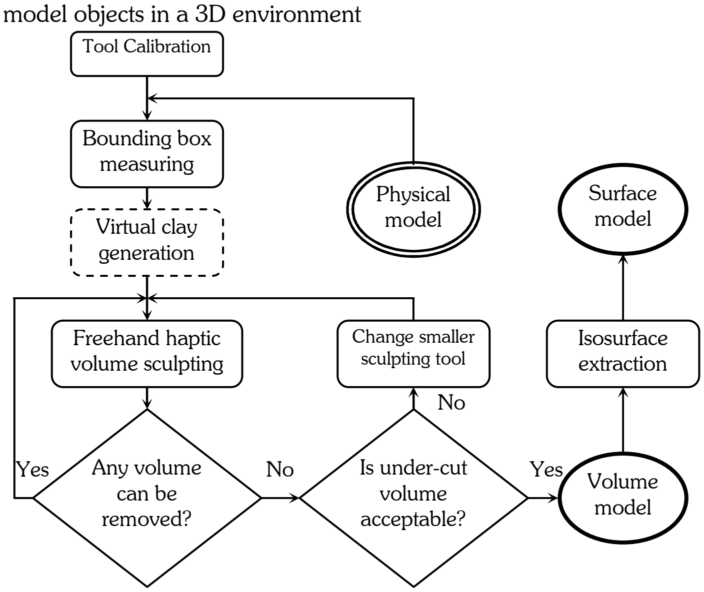
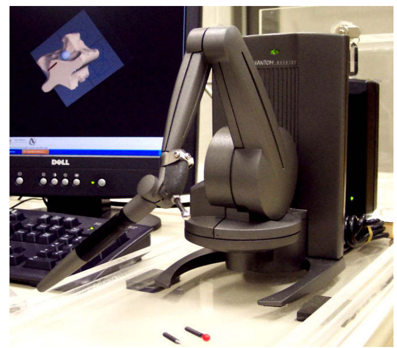


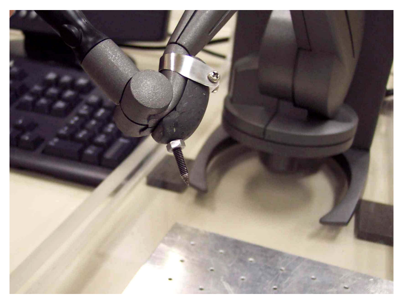
Fig. 4. Flow chart of the RE method by volume sculpting

that is similar to a natural setting. One of the most important issues in haptic shape modeling is haptic rendering. In order to create a touchable environment, many haptic rendering methodologies have been developed. Although most of the researches of haptic rendering are focused on surface representation objects, algorithms on haptic rendering of voxel-based objects can be found.

The benefits of haptic rendering of volume data was recognized by Iwata *et al*. [13], though it is not fully discussed. Avila *et al*. presented a haptic interaction method that point contact forces are computed directly from the volume data and are consistent with the isosurface and volume rendering methods [14]. They developed a set of virtual tools, whose position and orientation is simulated by a PHANToM® haptic interface to edit the volume model. However, their intent is to convey more information of volume dataset to users but not to provide realistic force feedback. A physics-based modeling system was reported in [15]. Dynamic subdivision solids respond to applied forces and give the user the illusion of manipulating semi-elastic virtual clay. They also developed a sculpting system that provides an intuitive sculpting toolkit. An application of haptic volume sculpting to surgical simulation was recently reported by Petersik *et al*. [16]. They proposed a multi-points collision detection method to generate realistic force feedback. A commercially available physically-based shape modeling system is FreeForm® released by SensAble® Technologies. As shown in Fig. 3, users can create digital models in an intuitive and direct manner as



(a) PHANToM® with a probe (dm=6.5 mm)



(b) Close-up of the probe (dm=0.5 mm)

Fig. 5. PHANToM® attached with a digitizing probe

physical modeling with clay or wax while taking advantage of the flexibility and efficiency provided by a digital environment [17].

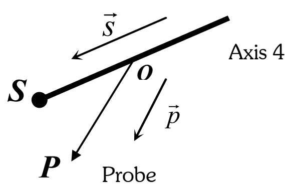
3. REVERSE ENGINEERING BY VIRTUAL VOLUME SCULPTING

The techniques reviewed above are synthesized in this paper to construct a new process of reverse engineering. The flow chart of the proposed RE method is shown in Fig. 4. After the tool is calibrated, the physical model is fixed in the workspace of the digitizer. In our archetypal implementation, as shown in Fig. 5, the digitizer is a refitted PHANToM® Desktop with a probe assembly attached to its arm. The PHANToM® has a nominal position sensing resolution 0.02 *mm*. It is then used to measure the bounding box of the physical model with the aid of a dedicated fixture.

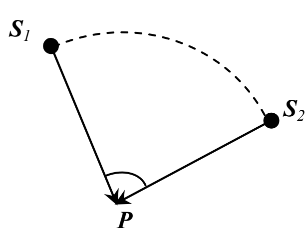
According to the obtained bounding box, virtual clay is generated with a user-defined voxel resolution. The resolution can be adjusted in subsequent operations. This virtual clay is the raw material block. Users start to remove volume from the virtual clay with the probe in a freehand manner. This operation is repeated until no more volume can be removed by this tool. Under-cut will occur because of tool inaccessibility when the curvature radii of a geometric feature are smaller than the probe tip radius. If the under-cut volume is not acceptable, a smaller probe tip will be used instead to remove the under-cut. When there is no more volume can be removed by the smallest tool, the residual virtual clay is a voxel representation of the physical object. If a surface model is desired, e.g. for rapid prototyping, isosurface extraction algorithms can be employed to generate a surface representation from the volume model.

3.1 System Configuration

A set of material removing tools with different effective shapes can be designed for efficient material removal. At present stage, 3 ball-head probes are manufactured with the diameters (dm) of 6.5 *mm*, 6.0 *mm*, and 0.5 *mm*. The bigger probe can achieve larger material removal rate, but under-cut volume left is larger. While the smaller one removes material more slowly but more precisely.



(a) Calculation of probe head centre position

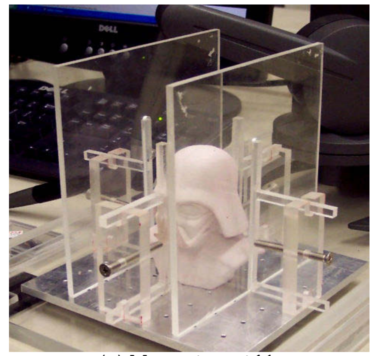


(b) Measurement of |SP|

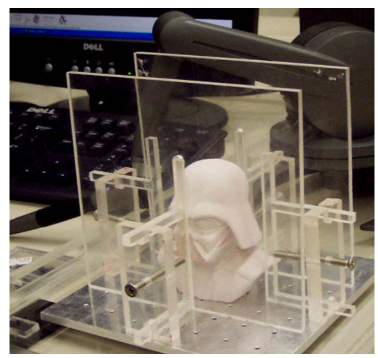
Fig. 6. Calculation of probe head centre position

The PHANToM® Desktop can return the orientation of the PHANToM® arm and the position of haptic interface point (HIP). Since the relative position between the HIP and the probe tip is nonlinear, it is necessary to get the relationship between the probe tip position and the HIP.

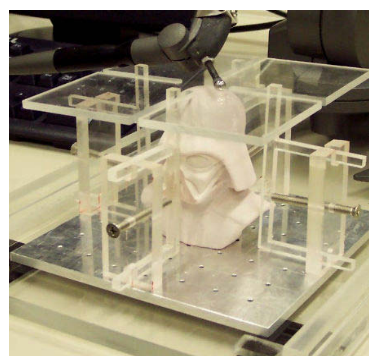
Similar to an articulated robot arm, the PHANToM® device consists of 6 axes. From the base to the stylus, they are labeled as axis 1 to axis 6. Axis 3 and axis 4 are coincident. As modeled in Fig. 6, the probe is fixed on the axis 4 of the PHANToM® Desktop. Point P is the



(a) Measuring width



(b) Measuring length



(c) Measuring height

Fig. 7. Bounding box estimation

center of the probe tip. Point S is the HIP, whose position is obtained by calling GHOST® API function. $\vec{s}$ is the orientation vectors of PHANToM® axis 4 (also the axis 3). $\vec{p}$ is the direction vector from the attaching point O pointing to probe tip P. Vector **OP** may rotate around vector $\vec{s}$ during digitization. Therefore, the coordinate of P is determined by the position of S and the orientation and length of $\overrightarrow{SP}$. P can be calculated by the following equation:

$$\boldsymbol{P} = \boldsymbol{S} + \left\|\overline{SP}\right\| \times \vec{s} \tag{1}$$

where $\left\|\overline{SP}\right\|$ is the distance from point $\boldsymbol{S}$ to point $\boldsymbol{P}$. The direction of $\overrightarrow{SP}$ is computed from the PHANToM® axis angles. In order to obtain the length of $\overrightarrow{SP}$, we measure a fixed point in world coordinate system twice. The orientation of probe varies in each measurement. As illustrated in Fig. 7, $\boldsymbol{S}_1$ and $\boldsymbol{S}_2$ are the returned stylus tip position. The position of $\boldsymbol{S}_1$ and $\boldsymbol{S}_2$ and the directions of $\overline{S_1P}$ and $\overline{S_2P}$ can be obtained by calling API functions. Thus, $\overrightarrow{SP}$ can be calculated. After compensating the radius of the probe head, the coordinates of the contact point can be calculated from the HIP.

3.2 Virtual Clay Generation

The virtual clay generated should be just big enough to enclose the object to be digitized. Therefore, a dedicated fixture is designed to ensure a proper bounding box of the given physical object can be obtained.

As illustrated in Fig. 7, the bounding box measurement is carried out in four steps: first, fix the object on the supporting plate and push the 4 guiding pillars to contact the object tightly; second, use the two sliding plates to measure the width of the object; third, use the two sliding plate to measure the length of the object; use one sliding plates to measure the height of the object. By this method, the generated virtual clay is automatically registered to the bounding box of the physical object.

3.3 Haptic Rendering

Mass-spring model is widely used to represent the models with elastic characteristics. In that model, force is defined as a function of penetration depth and velocity. While in volume sculpting, the basic mechanism is material removing. A cutting force is applied to the material such that the local stress exceeds the yield stress of the material resulting in plastic deformation and shearing of the material along the shear plane angle. To reflect the force in plastic deformation, a volume-based haptic rendering of milling process is developed by the authors for a haptic shape modeling system [17]. The force is defined as a function of material removal rate. The reported force model is simplified to fit in the application presented in this paper.

In the implemented prototype system, a simple force model associated with "voxel removal rate" is used. Since a realistic force model is neither easy to fulfill nor prerequisite in this application, the force generated is defined as proportional to the number of voxel removed within one haptic cycle, *i.e.*, voxel removal rate.

In order to meet the requirement of achieving a stable force feedback, the haptic period is usually less than 1 ms. Assuming the velocity of the probe is 100 *mm/s*, the displacement of the probe in one haptic cycle is less than 0.1 mm. Based on this observation, we use linear interpolation to estimate the swept volume of the probe in one haptic cycle. As illustrated in Fig. 8(a), the radius of probe head is denoted by r. Let $\boldsymbol{P}_1$ (x_1, y_1, z_1) and $\boldsymbol{P}_2$ (x_2, y_2, z_2) be the positions of the probe head centre at time t and time $t+\Delta t$ respectively, where Δt is the haptic period. Without losing generality, we assume $x_1 < x_2$ and $y_1 < y_2$. The swept volume consists of three parts: the volume occupation of the probe head at time t and $t+\Delta t$, the cylinder defined by: the top and bottom circles are centred at $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$, and their radii are r; the axis is along $\overline{P_1P_2}$. Let $\boldsymbol{Q}(x, y, z)$ denote the centre of a voxel as shown in Fig. 8(b). The voxel will be removed if the following condition is satisfied:

$$\begin{cases} \left\|\overline{P_1Q}\right\| < r; or \\ \left\|\overline{P_2Q}\right\| < r; or \\ (d_1 > 0) and (d_2 < 0) and (d < r) \end{cases} \tag{2}$$

where d_1 and d_2 are the directional distance from $\boldsymbol{Q}$ to the bottom and top circles, respectively, and $d = \frac{\left\|\overline{P_1Q} \times \overline{P_1P_2}\right\|}{\left\|\overline{P_1P_2}\right\|}$.

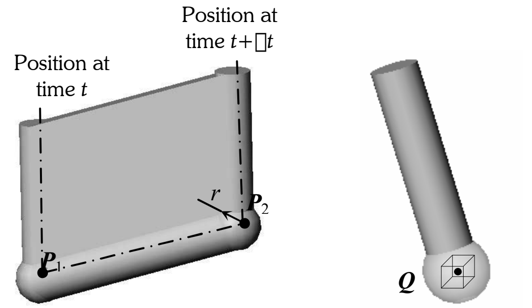
Assuming the number of the voxels that need to be removed within one haptic cycle is **N**. The force F fed back to the user is calculated as:

$$F = k\mathbf{N} \tag{3}$$

where k is a constant reflecting the hardness of the virtual clay and adjustable by the users. If k is set to zero, no force feedback is generated. Usually, k is set to be small at the preliminary stage of sculpting at which fast material removal is desired. While it is set to be larger at the finishing stage, because that voxel removal rate is quite small and force generated is unperceivable. The direction of the feedback force is always opposite to $\overline{P_1P_2}$. The force model used here is quite simple but practical.

3.4 Volume Sculpting

In our application, the object is represented by a volumetric data structure called Spatial Run-Length Encoding (S-RLE) developed by the authors. S-RLE consists of two cross-referenced database: one is a stack of lists in geometrical domain, recording the runs describing the space occupation of the object; the other is a table in physical domain, describing the physical properties of each element. The former is called position array and the latter property list. The property list is extendable to include more physical properties and to represent heterogeneous objects. For the time being, only one kind of sculpting operation is needed and implemented: material removing. The element operation of material removing is to remove a voxel.



(a) Swept volume in one haptic cycle

(b) Voxel to be removed

Fig. 8. Swept volume of probe head

In geometric domain, S-RLE is analogous to 2D run-length encoding (RLE). A volumetric 3D object in a 3D space $\boldsymbol{W}$ is denoted by $\boldsymbol{V}$. A run is denoted as $z = z_k$, $y = y_j$: (x_{start}, x_{end}), where (x_{start}, y_j, z_k) and (x_{end}, y_j, z_k) are the start voxel and end voxel respectively, or in a concise format: (z_k, y_j: x_{start}, x_{end}). Assuming a given voxel $p(x, y, z) \in \boldsymbol{V}$, and its containing run is R, removing a voxel $p(x, y, z)$ results in two cases:

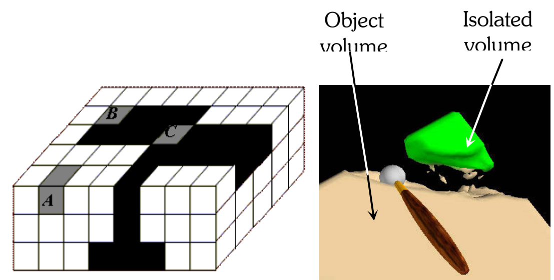
- p is the head or tail voxel of a run R (as the voxel ***B*** shown in Fig. 10(a)). The removal of voxel p will shorten the run by one voxel;
- p is neither the head nor the tail voxel of a run R (as the voxel ***C*** shown in Fig. 10(a)). The removing operation will break R into two runs.

The pseudo-code algorithm is as following:

***Algorithm* 1**. Removing(p, $\boldsymbol{V}$)
int ret = 0; /*integer return value indicates which case occurs when inserting current voxel*/
$R(u', u'': v, w)$ = locating (p, $\boldsymbol{V}$); //locating p
if($R(u', u'': v, w)$!= null) //$p \in \boldsymbol{V}$
{if ($\exists$ ($R(u', u'': v, w) \in \boldsymbol{V}$) satisfying $x= u'$)/*p is the head voxel*/
{replace R with (u'+1, u'': v, w); /*shorten the run*/
ret = 1; //case 1 occurs;}
else if ($\exists$ ($R(u', u'': v, w) \in \boldsymbol{V}$) satisfying $x= u''$) /* p is the tail voxel*/
{replace R with (u', u''-1: v, w); /*shorten the run*/
ret = 1; //case 1 occurs}
else {remove run $R(u', u'': v, w)$;
add run $R_1(u', x : v, w)$ into $\boldsymbol{V}$;
add run $R_2(x, u'': v, w)$ into $\boldsymbol{V}$; /*break R into R_1 and R_2*/
ret = 2; //case 2 occurs}
}
else {ret = 3;} /* $p \notin \boldsymbol{V}$, removing operation failed*/

For example, the removing of voxel ***A*** shown in Fig. 9(a) will return a failure flag, since it doesn't belong to the object. More complex algorithms of removing a lump from the virtual clay can be derived from this voxel removing operation.

An auxiliary operation is defined to accelerate the material removing process: isolated volume removing. An isolated volume is generated when a portion of the virtual clay is separately completely with the "object-in-progress" volume, *i.e.*, the connectivity of the virtual clay is destroyed. As illustrated in Fig. 10(b), a lump of isolated volume is highlighted. Users may select the isolated volume and remove it by one click. It is noticed that there are some tiny isolated volumes in Fig. 9(b). Users may select the object volume first, and then crop all other isolated volumes.



(a) Voxel removing

(b) Isolated volume

Fig. 9. Volume sculpting

4. EXPERIMENTS

A prototype RE system based on the proposed methodology has been implemented. The hardware is introduced in previous sections. The software is written with VC++. GHOST® API is used to interface with PHANToM® for force rendering. The open source package VTK (Visualization Toolkit) is employed to do graphics related work. Based on the "callback" mechanism provide by GHOST®, a VTK wrapper around the gstForceFeedback class in the API is developed. In the callback function, self-developed class that implements the volume-based haptic rendering is called. In our experiments, the haptic update rate is sustained at 900Hz or higher. Such an update rate is achieved by the simplified force model and the haptic loop and graphic loop decoupling technique.

Several physical objects are "volume-copied" with the digitizing probe. Fig. 10(a) shows a physical object fixed in the workspace and virtual clay is generated to contain it. Measuring this object with CMM is very time-consuming because the probe orientation needs to be changed many times. What's more, a professional operator of CMM is required to do the path planning work. Fig. 10(b) shows virtual clay under sculpting, portion of the physical object is emerging. When sculpting process is going on, users can rotate the virtual clay to see if excessive volume exists. Users can also sensing the existence of excessive volume by haptic feedback. Fig. 10 (c) and (d) shows the voxel model and surface model of the outcome, respectively. Fig. 10(e) is the picture of its counterpart made by SLS machine. The sculpting time is less than 20 minutes by a layman of CAD/CAM. It is difficult to scan this object in such a short period using a manual contact measuring device, *e.g.* MicroScribe®.

5. DISCUSSIONS AND CONCLUSIONS

This paper has presented a novel reverse engineering methodology based on volume sculpting with the aid of haptic rendering technique. The method features point-cloud-free and freehand digitizing. Since there is no point cloud data as the intermediate representation, the post-processing is not a must, unless a surface model is desired. Freehand digitizing makes it available to a non-professional user.

Any 3D position tracker can be used as an agent to remove the excessive volume. However, we employed a haptic device to do the job. Some internal features are invisible from some points of view, but they are touchable. By using a haptic device, the number of view changes could be reduced and the operating time is shortened. What's more, the concurrent visual and haptic simulation provides the users an intuitive and user-friendly interface. The haptic cue is proved to be very helpful to decide whether or not any excessive volume is left.

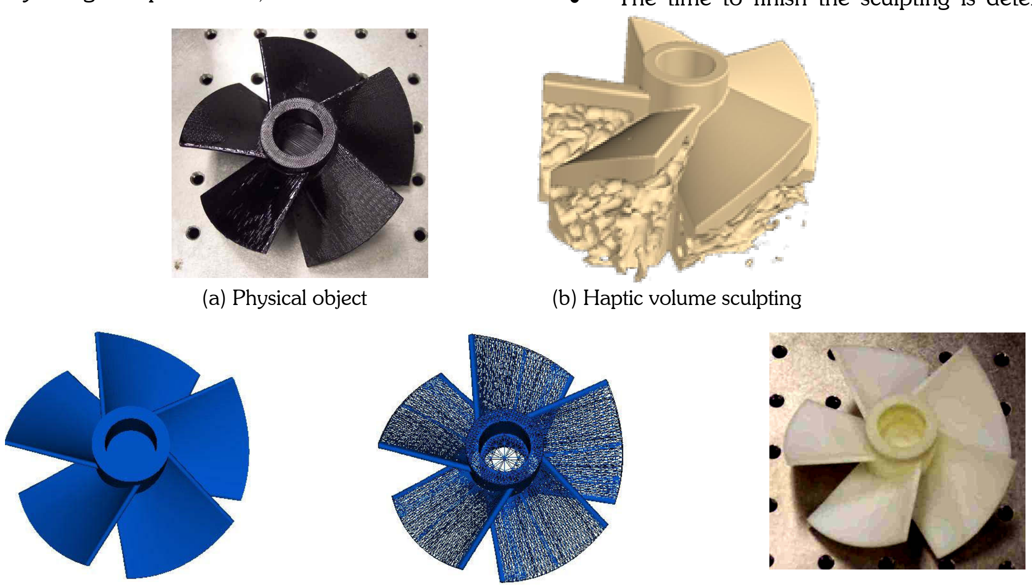
5.1 Advantage and Disadvantage

Compared to other RE methods, the proposed one has the following advantages:

- Redundant points from existing manual scanning system are avoided by voxel based visual feedback. While the model emerges gradually, the digitized surfaces are explicitly seen and used as a guide to the user.
- No need to use a switch to control the starting or stopping of position recording;
- No need to plan the scanning tool path;
- Freehand sculpting demands low operator skill;
- Volume representation is robust in contrast to point-edge-surface representation. Noise data is unlikely to be introduced;
- The RE method overcomes the shortcomings of laser scanning: transparent material, reflective surface, or some internal surfaces can be digitized as long as they are touchable.

However, disadvantages and limitations do exist in our method:

- They must make contact with the surface, just like any other contact measuring method, which may be undesirable for fragile or deformable objects;
- The time to finish the sculpting is determined



(a) Physical object (b) Haptic volume sculpting

(c) Voxel model (d) Surface model (e) Counterpart made by RP

Fig. 10. Experiment of haptic volume sculpting

by visual and haptic feedback, which may not be accurate;

- The accuracy of digitized model is mainly determined by the voxelization resolution of the virtual clay. There is a conflict between accuracy and real-time response;
- Probe accessibility has to be taken into account when objects with higher geometrical complexity and tiny concave or internal features.
- The size of the physical object that can be digitized is limited by the workspace of the sculpting device. The nominal workspace of PHANTOM® Desktop is $160\times130\times130$ mm^3, and that of PHANTOM® Premium 3.0 is $410\times590\times840$ mm^3. When a 3D tracker without force feedback is used as a sculpting tool, the workspace could be much larger.

5.2 Applicability

Since the proposed RE methodology is point-could-free, the post-processing after digitizing is quite simple. STL file can be easily obtained by isosurface extraction and triangulation. Therefore, the RE method is suitable for making a rapid prototyping copy of an existing object quickly.

As discussed in [18], reverse engineering can be used as an input tool of a conceptual engineering design system. The proposed RE method is easy to grasp by the designers without any professional geometrical modeling skills, such as artists, sculptors. What the designers need to do is locating the existing physical object within the PHANToM® work space and defining the position where he/she wants to put the digitized model.

5.3 Future works

The accuracy issue needs to be studied further. Level-of-details (LOD) techniques are envisioned to be helpful to improve the accuracy. We are considering a two-stage sculpting strategy: rough sculpting and finish sculpting. Large voxel size is used in roughing stage. The boundary voxels of the coarse model obtained by roughing are subdivided. The final accuracy is determined by the voxel resolution at finishing stage.

Sculpting tools with different shape need to be manufactured and defined to achieve better surface finish and higher material removal rate. For instance, a cubical tool may be more suitable for carving plane surfaces and right corners.

Physical constraints and virtual constraints coupling technique will be investigated further.

Acknowledgements

This research is supported by a grant from Hong Kong Research Grants Council under the code HKU 7073/02E.

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