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Automated Feature-Based Registration for Reverse Engineering of Human Models

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In order to reconstruct a full 3D human model in reverse engineering (RE), a 3D scanner needs to be placed arbitrarily around the target model to capture all part of the scanned surface. Then, acquired multiple scans must be registered and merged since each scanned data set taken from different position is just given in its own local co-ordinate system. The goal of the registration is to create a single model by aligning all individual scans. It usually consists of two sub-steps : rough and fine registration. The fine registration process can only be performed after an initial position is approximated through the rough registration. Hence an automated rough registration process is crucial to realize a completely automatic RE system. In this paper an automated rough registration method for aligning multiple scans of complex human face is presented. The proposed method automatically aligns the meshes of different scans with the information of features that are extracted from the estimated principal curvatures of triangular meshes of the human face. Then the roughly aligned scanned data sets are further precisely enhanced with a fine registration step with the recently popular Iterative Closest Point (ICP) algorithm. Some typical examples are presented and discussed to validate the proposed system.

Key Words : Reverse Engineering, Registration, Feature Extraction, Digital Human Model

1. Introduction

The recovery and representation of three-dimensional (3D) geometric shape of physical objects has been widely investigated in reverse engineering (RE). The RE process was defined by many researchers with respect to their specific applications. Sarkar and Menq (1991) described RE as a process of retrieving new geometry from a physical object by scanning the object. Jun (2005) concisely defined the RE process as the process to create digital or physical replicas of a target part. These definitions describe specific functions covered within the global term 'reverse engineering'. Recently, RE encompasses many engineering approaches in which an existing product is investigated either prior to or during the reconstruction process. It has been applied into various emerging applications such as custom-made manufacture, design simulation, medical, virtual reality, digital archeology and computer graphics. Especially, there has been an increasing demand for digital human models in RE applications where the complex and highly unique human surface must be recreated in order to obtain an exact fit a single product such as gloves, shoes,

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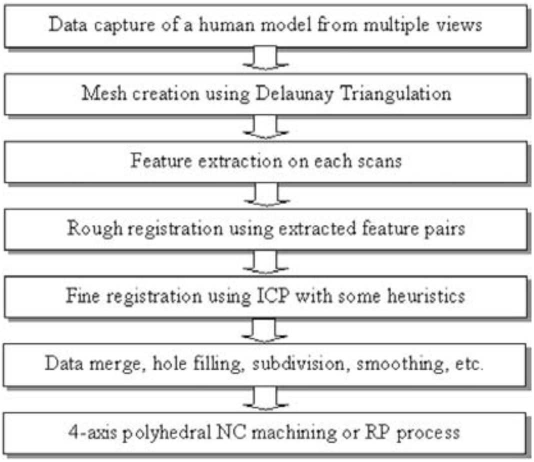

Fig. 1 Schematic diagram of the proposed RE system

helmets, replacement joint, sports wear in manufacturing. Also, it can be used in other numerous applications; for instance, interactive computer games, manufacturing simulation, medical training, and virtual surgery.

We have been building a dedicated RE system that automatically reconstructs human head and shoulder in a 3D bust. The system consists of a portable non-contact 3D scanner, a suite of various polygon-based data processing modules for triangulating, registering, merging, smoothing, subsividing, and re-meshing scanned data. Figure 1 shows the proposed RE procedure for automatically reconstructing of a human bust model.

It generally involves the phase of 1) data capture, 2) data registration and merge, and 3) model reconstruction (Jun et al., 2001; Roh et al., 2002). The RE process begins with a 3D positional scanner that captures the individual scans of a human model from several different point of views. This is because no single scan suffices to describe an entire object surface. These scans consist of several millions of scanned points and each data set is given in the scanner coordinate system. Registration process is to compute a rigid transformation that aligns all different data scans into a common frame of reference with the information of overlapping points. It consists of two sub-steps such as rough registration and fine registration. A major bottleneck in the process is the automated registration of a large number of scanned sets in a common frame of reference. There are lots of algorithms available to automatically perform the fine registration, but only after an initial position is approximated through the rough registration. These rough transforms give us a quite good approximation without preventing proper convergence in the next fine registration stage. Hence automatic rough registration step is crucial to realize a fully automatic RE system.

In this paper a rough registration method for automatically aligning multiple scans of complex human face is presented. The proposed method is based upon the information of features that are extracted from the estimated principal curvatures of triangular meshes of the human model. From the rough registration data, a fine registration module is then applied to further precisely align all roughly aligned scans to make a fully registered 3D model. Then, merging process stitches all registered sets into a common representation. Finally, NC tool-paths (STL data) are generated and transferred into a 4-axis CNC (rapid prototyping) machine to manufacture a physical replica. This paper presents two specific issues regarding efficient algorithm for aligning multiple 3D scans of complex human face as follows.

- Feature extraction algorithm based upon the estimated principal curvatures of scanned data.
- Rough registration algorithm that automatically computes pairwise registration between individual scans based upon the extracted features.

The remaining of this paper is organized as follows: In the following section many of the previous techniques associated with the feature-based technology and multi-view registration algorithms are briefly reviewed. In section 3 the data acquisition is presented which capture the surface details of a target model. More explanation on the feature technology and the proposed registration techniques are described in section 4 in details. The section 5 presents typical examples with discussion. Finally, this research work is concluded with necessary future works in section 6.

2. Related Work

Extracting the relevant feature information directly from scanned point set can be the first step to make a fully automated RE application. There has been lack of work regarding automatic feature extraction algorithm directly from scanned data. Some research works so far for extracting features have been intended to work with existing CAD models (Thompson, 1995). Our method is to register multiple different scans by extracting features from the raw scanned point cloud. The main idea of feature extraction is very similar to the following segmentation algorithms : polygon-based (Dickinson et al., 1994) and point-based approaches (Park et al., 2001). Polygon-based segmentation divides point data into connected regions of points according to some geometric properties. Typically, they grow regions around seed points. On the other hand, discontinuous edge points are first detected from the raw scanned points and then used to guide the segmentation process in the point-based segmentation. The feature extraction approach presented here is known as the hybrid approaches, since it refers to a combination of polygon- and point-based considerations. Some researchers (Chen et al., 1992 ; Zhang, 1994) do their own feature-based registration prior to refinement using such characteristics as positions of points with distinguishing principal curvatures on distinctive points.

Contrary to the feature extraction research works, there has been a great deal of interest in the process methodologies for registering multiple scanned data sets. Aligning two scanned sets after identifying two sets of corresponding 3D points can be done using a quaternion-based non-linear optimization method. Besl and McKay (1992) first introduced the process of establishing point correspondences from different scans. This is widely applied to ICP algorithm that repeatedly aligns two meshes by pairing points in one mesh with nearby points in the other from an initial set of corresponding points. This process is iterated over all the scans until the deviation of incremental motions is within a given convergence criterion. Other approaches to registration of multiple scans were based on matching discrete features (Wada, 1993). There are other problems in the basic iterative aligning algorithms such as huge memory, local minima, and computational expense (Eggert et al., 1998). Recently, Lee et al. (2005) studied the observability analysis of registration error with a multi-antenna GPS measurement system.

3. Data Capture

Until recently many 3D scanners have been developed to scan the surfaces of a target part. Due to the almost infinite range of shapes to be scanned with great differences in requirements concerning their accuracy and surface conditions, a great variety of scanning methods have been evolved. Hence the 3D scanners must be carefully selected according to their strengths and weaknesses.

In order to scan geometric information of a human model, the employed scanner should quickly capture the surface details since the 3D scanning process is sensitive to the movement of the human model such as varying facial expression or moving the head. Another prerequisite is the intensity of the adopted light source, so it must be comfort and safe to a human eyes and skin. Hence, laser-free optical-based scanners are suitable to scan a human with relatively fast capture rates. The scanner usually captures a cloud of points several times from different viewpoints

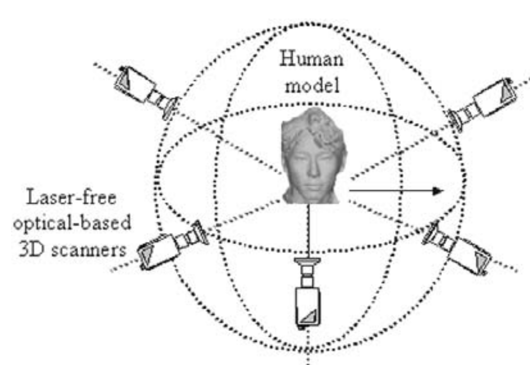

Fig. 2 Multiple scans from several different viewpoints

until whole geometry is adequately acquired as shown in Fig. 2.

4. Data Registration

Each scanned point set captured from several different points of view is given in its own local co-ordinate system. Hence, these scans need to be transformed into one global co-ordinate system and are adjusted to be aligned each other. The parameters of a transformation matrix must be determined by an accurate localization method. This whole step is denoted as registration process as shown in Fig. 3.

The whole registration process to align several individual scans consists of following sub-steps :

(1) Step 1 : rough registration : initially positioning of multiple scans in single co-ordinate system based upon the extracted feature information on each scan ;

(2) Step 2 : fine registration : further enhancing the roughly aligned positions ;

(3) Step 3 : merging : combining all aligned scans into one single model.

The fine registration and the merging processes (Step 2 & 3) can be automatically carried out after initial positions are determined through the rough registration stage (Step 1). If the initial position of a scan differs too much from the other, it is difficult to construct an accurate model. Currently, the most critical limitation to achieve a fully automatic RE system is mainly related to the rough registration stage. That is why we tackle the crucial issue of automated rough registration methodology. More detailed procedures are described in the following sub-sections.

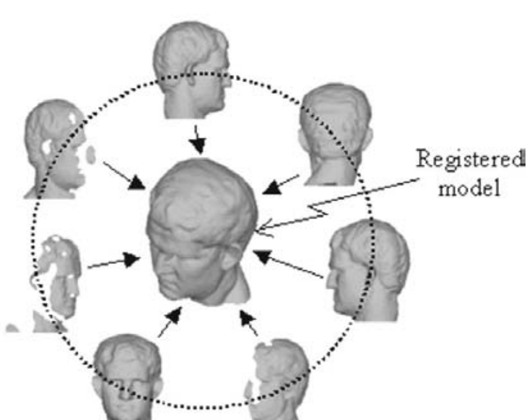

Fig. 3 Example of registration process (seven individual scans and their registered model)

4.1 Rough registration with feature matching

If all scans are captured using a precision motion device, the rough registration can be readily carried out from the accurate relative positional information between the scanned object and employed scanner(s) using motion-control hardware and software. However this kind of system is not cost-effective since inexpensive motion-control devices are usually limited to one or two degrees of freedom at most. Generally, a solution to the automated rough registration is possible if two pairs of matched geometric features are searched between the two scans. However, it is very time-consuming to form feature pairs between two overlapping surfaces. In this paper, to speed up the process, the proposed rough registration algorithm is based upon the face-specific features. The features are defined in terms of higher dimensional feature vectors, such as the estimated principal curvatures of the scanned surface. We choose a typical invariant feature set from the scanned point data as follows.

4.1.1 Face features

The best features on a human face need to be determined with the information of the principal curvatures that are hardly affected by facial expression change, and have a good correspondence with features in other scans. Particularly, the following features are mainly extracted as corresponding features : eye corner cavities, forehead boundary, nose boundary, nose base, mouth boundary, and so on. Figure 4 shows several extracted features directly from a scanned point set.

4.1.2 Feature extraction

In order to extract features, the curvature on a given point must be approximated first. There are

(a) (b)

Fig. 4 Automated feature extraction on front view. (a) Scanned points and face features (① forehead boundary, ② eye corner cavities, ③ nose boundary and base, ④ mouth boundary); (b) detected face features

several ways to approximate the curvature of a triangle mesh created from scanned points. The first idea is that the curvature is the limit of the area of the spherical image of the path divided by the area of the path around the point (Kreysig, 1991). That is, the ratio of the area of all triangles n_i n_o n_{i+1} over the area of all the triangles V_i OV_{i+1} is an approximation to the curvature at O as shown in Fig. 5.

The second method is known as angle deficit method (Calladine, 1986). As shown in Fig. 6,

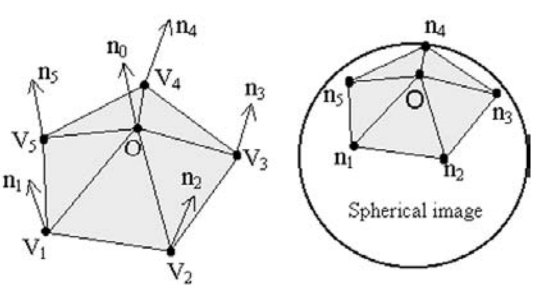

Fig. 5 Sperical image method (Kreysig, 1991)

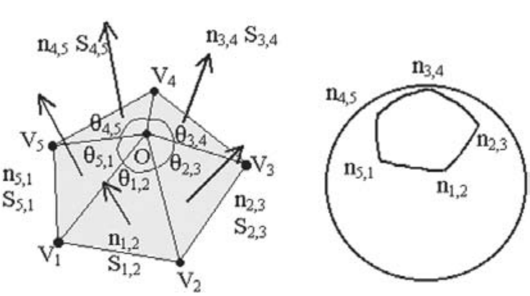

Fig. 6 The angle deficit of the polyhedron (Calladine, 1986)

the vertex O is surrounded by the triangles V_i OV_{i+1}. The spherical image of the polyhedron is a set of points on the unit sphere. The area of the spherical polygon is the angle deficit of the polyhedron, $2\pi-\sum\theta_{i,i+1}$. The area of each triangle can be partitioned into three equal parts, so that the total area related to point O on the polyhedron is $(\sum S_{i,i+1})/3$. This value is taken as an approximation to the area of a path on the surface around O. That is, an approximation to the curvature at O is shown in Eq. (1).

$$\rho=\frac{2\pi-\sum\theta_{i,i+1}}{\frac{1}{3}\sum S_{i,i+1}} \tag{1}$$

The normal of each feature point is also calculated to evaluate the certainty of feature point. By averaging the normals of neighboring triangles, normal to feature points are derived. A weight is then defined to each feature point to represent variations in certainty across the scans. For a sample feature point on the scan, weight w_{ij} is defined as Eq. (2)

$$w_{ij}=\frac{\bar{n}_{ij}\cdot\bar{n}_s}{d} \tag{2}$$

where $\bar{n}_{ij}$ is the unit normal of each feature point; $\bar{n}_s$ is the directional vector from the feature point to the scanner; and d is the distance between the point and the scanner (Li, 2000). The smaller the angle between these two vectors, the higher the certainty. Feature data at the boundaries typically have greater uncertainty and hence have less weight. Therefore any feature data at the boundaries can be automatically discarded from the feature list.

4.1.3 Overlapping area of two neighboring scans

The more overlapping regions in 3D data sets they are, the more accurate registration is accomplished. Hence, multiple scanned sets have significant overlaps with each other. Overlapping area between two neighboring scans is characterized by feature pairs in the 3D Euclidean space. The rough registration algorithm takes two sets of features sampled from the area of overlap, one set for each scan. The features in one scan are

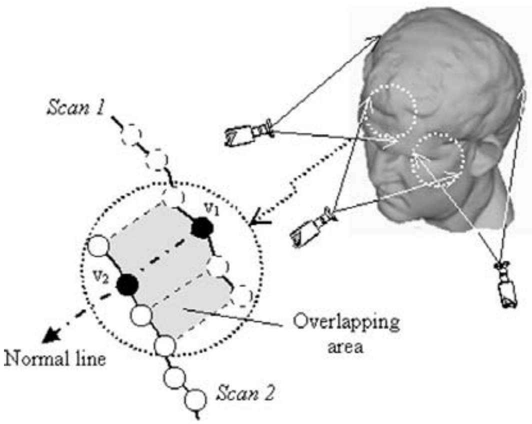

Fig. 7 Finding feature pairs in overlapping area

put into one list, and the other list contains their ideal feature pairs. The procedure to compute the ideal feature pairs is as follows. As shown in Fig. 7, scan 1 and scan 2 are two meshes of a person from two different views with overlap. In order to find the point v_2 on scan 2 corresponding to a point v_1 on scan 1, each triangle mesh to scan 1 and scan 2 need to be tested.

The normal line of a point v_1 on scan 1 is extended enough to intersect with the mesh of scan 2, and then the coordinates of intersection point are computed. The intersection point locates inside a triangle in scan 2. This process is iterated with the same manner until all scanned points on scan 1 are tested, so that the overlapping area can be found by checking the occurrence of intersection.

4.1.4 Feature matching

The feature matching is the process of comparison between two extracted features which belong to two scans respectively. Each pair is correspondent to approximately same position on a target person's face. The set of features associated with curvature data can be considered as a vector in feature space. Feature matching is the problem of corresponding points on the basis of some similarity pattern. This method is reasonable because matching between two different correspondences is made on the basis of a small number of feature measures. In order to use the feature vector as an effective basis of feature matching, all the points in feature space which correspond to nearly the same position on the face should be grouped with regard to some similarity manner. In this paper the input to the algorithm is a set of extracted features with the information of s-milarity such as the coordinates of feature points and relative distance between features. The distance of a feature in one scan is compared with other features from a different view. The error between two feature sets is computed and analyzed. If the error is within a given criterion, two features are recorded as corresponding feature pair. On the other hand, if the error exceeds the criterion, no feature is considered to belong to the feature corresponding list (Hallinan, 1999). With the above information, the individual scans are roughly registered with one another.

Consequently, the rough registration algorithm automatically determines the starting transformations of all the corresponding feature pairs. Inevitably, due to the error of extracted features, the rough registration is not exact but just approximate. However, these transforms give us a quite good approximation with proper convergence in the next fine registration stage for more accuracy.

4.2 ICP-based fine registration

The fine registration task involves finding the translation and rotation components of a transformation matrix that exactly align the roughly registered scans. This task is usually based upon the general Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992). Mathematically, the ICP-based registration is applied using an iterative process that can align the triangle meshes by minimizing the deviations between the roughly aligned scans. All ICP-based methods require the meshes to be spatially close with respect to each other after applying all the feature pairs. In this paper, some heuristics constraints are additionally imposed to overcome the major limitation of the general ICP that one scan must be a subset of the other. The modified ICP-based registration algorithm finds a transformation matrix that precisely aligns one roughly registered scan to another. Detailede crucial description is given as follows.

In order to find an accurate transformation matrix that precisely aligns all the roughly aligned scans, least square distance between neighboring point pairs are then computed according to the following Eqs. (3) ~ (7).

$$Distance = \sum \| \boldsymbol{A}_i - \boldsymbol{R}(\boldsymbol{B}_i - \boldsymbol{\mu B}_c) - \boldsymbol{T} - \boldsymbol{B}_c \|^2 \quad (3)$$

where $\boldsymbol{A}_i$ and $\boldsymbol{B}_i$ are point pairs on scan 1 and scan 2, respectively, and $\boldsymbol{\mu B}_c$ is the 'center of mass' of the $\boldsymbol{B}_i$. $\boldsymbol{T}$ is a translation vector and $\boldsymbol{R}$ is a rotation matrix. $\boldsymbol{T}$ can be calculated by :

$$\boldsymbol{T} = \boldsymbol{\mu A}_c - \boldsymbol{\mu B}_c \quad (4)$$

Since $\boldsymbol{T}$ is the difference of the 'center of mass' of point pairs between scan 1 and scan 2. The rotation matrix $\boldsymbol{R}$ can be determined by a unit quaternion according to the following subsequent steps.

(Step 1) Covariance matrix is computed by :

$$Cov. = \frac{1}{n}\sum_{i=1}^{n}[(\boldsymbol{B}_i - \boldsymbol{\mu B}_c)(\boldsymbol{A}_i - \boldsymbol{\mu A}_c)^T] = \begin{bmatrix} Cxx & Cxy & Cxz \\ Cyx & Cyy & Cyz \\ Czx & Czy & Czz \end{bmatrix} \quad (5)$$

where n is the number of point pairs.

(Step 2) From the Eq. (4), the $\boldsymbol{Q}$ matrix is derived :

$$\boldsymbol{Q} = \begin{bmatrix} Cxx+Cyy+Czz & Cyz-Czy & Czx-Cxz & Cyz-Czy \\ Cyz-Czy & Cxx-Cyy-Czz & Cxy+Cyx & Czx-Cxz \\ Czx-Cxz & Cxy+Cyx & Cyy-Cxx-Czz & Cyz-Czy \\ Cxy-Cyx & Czx+Cxz & Cyz+Czy & Czz-Cxx-Cyy \end{bmatrix} \quad (6)$$

Unit eigenvector $\boldsymbol{P} = [q_0\ q_1\ q_2\ q_3]^T$ corresponding to the maximum eigenvalue of matrix $\boldsymbol{Q}$ is selected as the optimal rotation.

(Step 3) Finally, a rotational matrix $\boldsymbol{R}$ is derived by :

$$\boldsymbol{R} = \begin{bmatrix} q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2 \end{bmatrix} \quad (7)$$

Above steps are iterated until the convergence is achieved. Then the second scan is precisely transformed to align with the first scan. More detailed mathematical procedure is described and discussed in (Besl and McKay, 1992). All of the ICP algorithms must use some set of criteria to check convergence of the final transformation. Final convergence is detected when the amount of motion is sufficiently small or the distance between point pair becomes suitably close. The algorithm can also be terminated if convergence is not reached after some maximal number of iterations.

4.3 Heuristics for registration

As mentioned in the previous section, there is one critical limitation in the original ICP algorithm that every point on one scan has a corresponding point on the other scan. That is, one of the data sets must be a subset of the other. This is a very tight limitation, because any single scan in multiple viewpoints does not fully contain other views. To overcome the limitation, some heuristics constraints are imposed as follows. Firstly, any point pair that is too far apart from others is discarded. This is the most fundamental heuristic to help proper registration process. Secondly, a point pair is also discarded if the closest point on the other scan is on a mesh boundary. This constraint was added because many points that are not in the overlapping area in one scan may match to boundary points in the other during the computation of the closest point. Final constraint is that all point pairs which intrinsic properties such as distance or normal vector are totally different with those of neighboring pairs are also discarded (Turk and Levoy, 1994).

4.4 Data merge and hole-filling

After aligning all triangular meshes using the registration process, the final step is to integrate all the aligned meshes into one combined single mesh that completely describes a human model with its topological information. The detailed algorithm of general merging process is quite straightforward. Turk and Levoy (1994) proposed an incremental method of merging multiple scans into one triangular mesh. Merging triangle meshes are composed of three subsequent tasks as follows :

(1) Removing overlapping areas;
(2) Trimming one mesh against the other;
(3) Regenerating both boundary meshes.

The above algorithm was implemented in the proposed RE system. The full topology of a merged mesh is constructed by consecutively stitching new scan sets into the first triangular mesh. That is, after a master scan is chosen, other scans are merged into it consecutively.

However the initial merged triangular mesh is not directly suitable for further downstream activities such as NC machining, rapid prototyping or FEM analysis. This is because it is not possible to acquire all part of the human bust since a human face is very complex with cavities and other small sized concave region. The missed triangles need to be filled and connected to form a continuous shape. Holes are filled with flat triangles first with subdivision operation and then smoothed with any other triangles in their vicinity (Jun, 2005). Through this work, various triangle-based functions such as sampling, reshaping, smoothing, subdividing, and decimation are developed. However, we skip the detailed algorithms of above functions because it is beyond the scope of this paper.

5. Implementation and Examples

The system reconstructs a digital human model by automatically carrying out the registration of a human head in a 3D bust. The graphic user interface and the visualization of the model geometry were written in C++ with OpenGL™ graphic library and currently run on the Windows systems. The C++ Standard Template Library was also used to efficiently describe the algorithms for a fast implementation. For the internal geometry representation, an application program interface (API) kernel was written and used. A Rexscan™, a 3D scanning device by Solutionix, Inc., was used to scan a human model. The scanner is a dedicated stand-alone unit, designed specifically for high speed data capture of complex 2D and 3D physical shape. It has a nominal scanning accuracy ±50 microns under optimal conditions, but it depends on the nature and shape of a part surface in practice. The scanner has some strong points to scan human faces. The light adopted in the scanner is not harmful to human eyes and is capable of scanning human hair as well.

Two typical examples of reconstructing human models are presented to assess the proposed system and methods. The first example shows the result of the proposed feature extraction module from the scanned points of a person's face as shown in Fig. 8.

The employed 3D scanner is based upon the structured lighting which involves projecting patterns of light upon the surface of a human bust and capturing an image of the resulting pattern as reflected by the surface. The light pattern modulated by the height variation of the face is illustrated in Fig. 8(a). A cloud of 3D points which is the output of the scanning system is shown in 8(b). The number of point data was 115,857. The 3D point cloud was further processed into a triangular surface model after sampling noise and outlier by discarding triangles with an edge longer than a pre-defined distance threshold as shown in 8(c). Figure 8(d) shows the extracted feature of the face using the developed feature extraction module. In this example, only one view

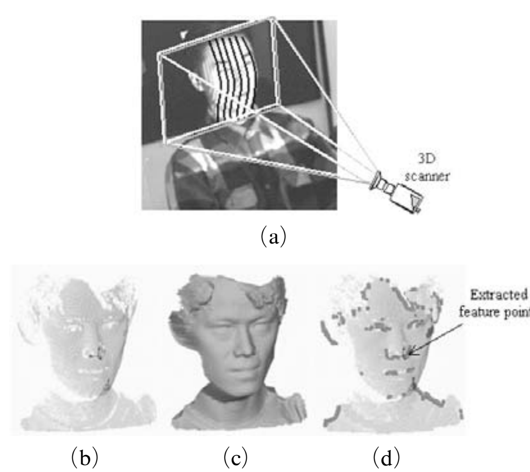

Fig. 8 The process of the reverse engineering system. (a) Projected light pattern; (b) scanned point cloud; (c) shaded image of created triangles; (d) extracted features

of the human model was scanned to represent the front view of the face to just validate the feature extraction module and therefore registration of scanned surfaces from different views were not required. The feature extraction method involves interpreting the curvature of scanned point clouds. Clearly, it strongly depends on the quality of the scanned data. In order to reduce the negative effect of noise points, it is necessary to employ adequate noise-filtering methods prior to feature extraction since the computation of curvature value is noise sensitive.

The second example shows the full process of reconstructing a 3D digital human model. A person was scanned in eleven different views. Figure 9(a) shows a registration result with arbitrary three scans to validate the rough registration process based upon the information of extracted features. The extracted features were used as an input to the rough registration module. This registration process is satisfied in the sense that the relative registration computation of the overlapping area can be obtained. It is clear from the figure that the polygonal surfaces of different views are successfully aligned with the feature information. The rough aligned position of feature pairs was then applied to the fine registration module to further precisely register the roughly aligned data sets. In the same manner, Fig. 9(b) illustrates the result of whole registration process with eleven individual scans. Then the merging module was applied to stitch all the aligned data sets into one master model. However the aligned and merged model contained some missing data causing polygonal holes since a human face is normally occluded with cavities and other small sized concave region. In order to eliminate all these holes, a hole-filling module was applied to fill the missing part as illustrated in Fig. 9(c). Due to the registration and merging errors the polygons did not match perfectly. So after merging, the polygonal mesh was distorted and need to be smoothed several times. The final step in this RE process was to manufacture a replica on the reconstructed geometric model generated from the previous procedures. In this research, the manufacturing process was carried out using

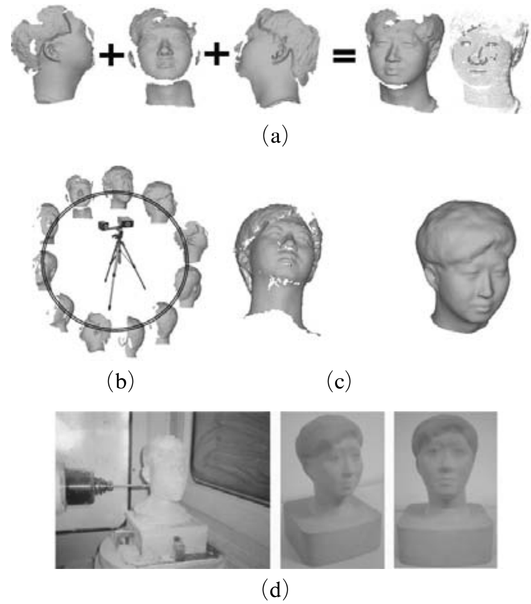

Fig. 9 Example of full 3D reverse engineering process. (a) Three individual views and their roughly aligned result; (b) eleven individual views and their roughly aligned result using extracted feature information; (c) Final model after applying hole-filling, smoothing, remeshing processes, etc; (d) 4-axis NC machining and a physical replica (bust sculpture)

a 4-axis NC machine. Figure 9(d) shows the photos of machining process and its scaled bust sculpture of the human model. The developed tool-path generation module was based upon polyhedral machining techniques from the reconstructed polygonal meshes.

The level of quality of the reverse engineered model is directly related the inaccuracies of the inherent noise of the scanner, the sampling resolution between data points, the error in the registration transformation, the error of machining process, and other polygon-based approximation modules such as smoothing and hole-filling. Errors were inevitably introduced and were cumulative. In order to compute the geometric differences between the original person and the machined replica, the part was inspected again using the 3D scanner. A number of reference points were compared to find the distance between each corresponding point pairs. From the results, the nominal dimensional error bound of the replica were within 0.2 mm~0.7 mm. The level of quality of the final model needs to be further improved by (1) improving scanning accuracy; (2) estimating exact curvature as a point correspondence feature; (3) automatically determining the next scans to capture more of target surface.

The basic techniques validated in this paper can be used where the complex and highly unique human surface must be recreated in order to obtain an exact fit for a replacement joint such as custom gloves, shoes, and helmets for individual have recently drawn great attention.

6. Conclusions

An automated RE system for reconstructing human models has been developed with the concept of a feature-based rough registration process. The system consists of five major parts: 1) the 3D scanning system based upon the principle of coded structured light, 2) feature extraction module, 3) automated registration and merge module, 4) polygon editing module including smoothing, hole filling, subdivision, and re-meshing, 5) computer-aided duplication module such as multi-axis NC machining system or RP system to duplicate a physical model from its triangular mesh.

We have mainly focused on the algorithm of rough registration based on the feature information, which makes a full 3D model from several viewpoints. The face features are defined in terms of higher dimensional feature vectors, such as the estimated principal curvatures of the scanned surface. The features in one scan are compared with other features in different scan. The meshes in different scans are automatically aligned from the information of extracted features. The fine registration algorithm employed in this work was based on the standard ICP algorithm equipped with some typical heuristics. These heuristics yield time saving, and perform a robust registration for various data sets very well. Current work was focused on the validity of the algorithm with robustness and efficiency. It is more crucial to concentrate on the development of solutions to specific problems within the RE process.

Acknowledgments

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