An Isomorphic Polygon Model for Describing Human Body Shape

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Abstract—A novel polygon model describing human body shape is developed. Firstly, a method of expressing an arbitrary point on a polygon mesh using the UV plane [9], [10] is proposed. An isomorphic feature of the model enables us to fit the polygon model to three-dimensional (3D) measurements by means of the least square method. Secondly, we efficiently allocate polygon vertices to trunk shape based on multiple sets of 3D measurements of Japanese women. The finally, derived generic model consists of 1,087 vertices and can reconstruct the original shape with the average error of 1.19 mm. This accuracy is sufficient for practical use.

Index Terms—body shape model, female trunk, isomorphic polygon model, and least square fitting.

I. INTRODUCTION

Human body measurements provide us basic information to understand shapes of our bodies necessary for designing a variety of everyday products. Body sizes (stature, girth of chest or abdomen, etc.) measured by Martin’s anthropometric method have been widely utilized. The body sizes, however, are not sufficient to describe three-dimensional (3D) shape of the human body. Besides measuring a lot of sizes by hand places mental and physical burdens on subjects and measurers, and frequently causes measurement errors. For these reasons, 3D measurement attracts a lot of attention as an accurate and high-speed method with the spread of laser metrology. HQL (Research Institute of Human Engineering for Quality Life) measured approximately 34,000 of people in Japan from 1992 to 1994 [1], and CAESAR (Civilian American and European Surface Anthropometry Resources) project collected about 6,000 of the 3D measurement data of civilians in U.S. and Europe from 1998 to 2001 [2]. They are well known as the mass-3D measurements, and also many institutes and corporations have carried out 3D measurement. However, it is difficult to analyze shape of the human body directly from 3D data because the data consist of a huge amount of surface points that have no correspondence among subjects. Therefore, a model of 3D shape of the body is necessary to convert 3D measurements into shape data that consist of a small number of parameters homologized among subjects.

In order to serve in a lot of applications including statistical analysis of 3D human body shape, a body shape model must satisfy the following four requirements: (1) the parameters of the model must have correspondence among different subjects; this property will be defined as “isomorphism” in Section II, (2) the model must be able to reconstruct the original shape with a sufficient degree of accuracy, (3) the number of parameters must be small enough to analyze, (4) a model describing local shape of the body can be extracted from the whole model. The number of parameters affects the minimum number of subjects to be prepared for statistical shape analysis, and also has exponential relation with the amount of calculation.

Many of models for describing human body shape have been developed. Some models relevant to this study are summarized below. The simplest is a polygon model using triangulation for describing a limited set of 3D measurements. Azouz et al. also proposed a method approximating 3D measurements with a polygon mesh using volume description [3]. These models enable to extract the surface information from the measurements. However, each vertex of the polygon model does not have the correspondence and the number of vertices still remains large. On the other hand Mochimaru [4] introduced Homologous Body Shape Model in order to guarantee the correspondence among the models of subject. This method deforms a generic polygon model roughly with anatomical and geometrical feature points on the body surface by the free form deformation (FFD) technique. And then the generic model is fitted to the measurements more accurately by using two energy functions based on the distance between polygon vertices connected by a line and the distance between a measurement point and its closest point on the polygon. Similar techniques combining the FFD with the iterative fitting process can be found in a breast model [5], and the model proposed by Allen et al. [6]. However these polygonal models do not provide quantitative description of points on the body except for the polygon vertices. Also the pre-defined shapes of the generic models constrain the resulting shape of the model.

Kurokawa and his colleagues proposed some human body shape models that are isomorphic and also satisfy the remaining three requirements (2), (3) and (4) [7]-[10]. One of them can describe trunk shape of woman with 750 control points of a B-spline surface normalized by 17 anatomical points [9], [10]. This model can reconstruct any point on the body surface with the average error of about 1.5 mm. We have already demonstrated that the model is useful to simulate brassiere-wearing figures [11], and to analyze 3D shape of the breast [12], the abdomen [13] and the trunk shape [14]. There are yet some problems with the B-spline model: It cannot be...
easily extended to the whole body, and implementation of desirable allocation of the control points are strongly restricted, because the B-spline surface is difficult freely to control even if we utilized a NURBS (non-uniform rational B-spline) surface.

This paper aims to develop a novel model of human body shape by combining the shape describing technique in the B-spline model [9], [10] suitable for statistical analysis and a polygonal mesh widely used as a shape approximation technique. Our new model also satisfies the requirements (2), (3) and (4). Two issues will be treated in this paper. The first is expression of points on polygon surface. We cannot treat points that do not exist on the mesh in ordinary polygon models. To address this problem, we will introduce a surface coordinate system into a polygon mesh. This enables us to fit the polygon model to the 3D measurements by the least square method. The second issue is efficient allocation of the polygon vertices to the body surface. We will show an approach to derive an efficient allocation of vertices using multiple data of women so that the resultant model can describe the body shape accurately with a small number of parameters.

II. ISOMORPHIC POLYGON MODEL

In this section, we explain methods of expressing points on a polygon mesh and of controlling vertices in case of female trunk shape that has comparatively large variability.

A. Expression of Points on Polygon Mesh

Adding surface coordinates to a polygon model enables us to treat all the points on the model as data. Here the UV plane [9], [10] plays an important role. In short, the UV plane is a mapping of measurement points onto a periodical cylinder-like surface normalized by the 17 anatomical feature points defined on women’s trunk surface; By normalization we mean that the 17 points have their own predetermined position on the UV plane (see APPENDIX). Our idea is that we define a triangular polygon mesh on the UV plane having the surface circumferential coordinate \( u \), and the height coordinate \( v \). This allows us to express any point on the model as a linear combination of the polygon vertices,

\[
p(u, v) = \sum_{i=1}^{T} Q_i(u,v)t_i.
\]

Where \( p \in \mathbb{R}^3 \) is a point on the UV plane mapped from one of the body surface measurements and has the \( u, v \) coordinate \((u, v)\). \( t_i \) is the \( i \)th vertex of the polygon model \((i = 1, ..., T)\). \( Q_i \) is an internal division ratio of each vertex of the triangle containing the \((u, v)\) point on UV plane as shown in Fig. 1. If all the triangles to which a vertex belong do not contain the \((u, v)\) point, the vertex has \( Q_i = 0 \). Thereby \( \sum Q_i = 1.0 \).

B. Generation of Triangular Polygon Model of Trunk Shape

Our polygon model can be generated through the three processes: vertex allocation, triangulation, and least square fitting as described below.

1) Vertex Allocation

We can allocate the polygon vertices to the trunk mapped onto the UV plane as shown in Fig. 2(a), where the distribution of the anatomical feature points on the UV plane helps us to understand the relation between the UV plane and parts of the trunk. The density of the vertices affects the model accuracy. A method for obtaining an efficient allocation of the polygon vertices is stated in Section III.
vertices allocated to a square grid as an example. Note that our generic model does not need to form any shape in $\mathbb{R}^3$ space before fitted to 3D measurements.

(3) Least Square Fitting

The model shape of any subject can be determined by the least square method. Modeling error is defined as the Euclidean distance between a measurement point $p$ and its corresponding point $p$ on the model surface,

$$e = \|p - p\| = \left\|p - \sum_{j=1}^{T} Q(u, v) t \right\|.$$

Then $x, y, z$ coordinates of each polygon vertex $t_i$ ($i = 1, ..., T$) are calculated to minimize the sum of the squared errors,

$$E = \sum_{j=1}^{T} e_j^2,$$

where $e_j$ stands for the error of the $j$th measurement.

C. Isomorphism of Polygon Model

Individual models obtained by fitting the same generic model to different subjects’ 3D data have one-to-one correspondence in all the vertices, although they differ in body shape. We can roughly hypothesize that this correspondence is held among points on body surface, too. That is, we can assume that the points having the surface coordinate $(u, v)$ on different model surfaces mean the identical point on the body surface in different subjects.

We would like to say that individual models having one-to-one correspondence are isomorphic and that our generic model and, therefore, its polygon mesh are also isomorphic. The property of isomorphism allows a variety of applications of the models as already described in [7]-[13] and [14].

Now we can utilize the $T$ vertices as shape data to describe body shape of the individual person.

III. EFFICIENT VERTEX ALLOCATION

In this section we present a method of efficiently allocating polygon vertices of the generic model explained in Section II in case of women’s trunk shape. Optimization of a polygon mesh to an object is one of the key issues in computer graphics. The number of parameters of a body shape model must be reduced while keeping the information on the original shape. A method to optimize a body model to an average shape using Gaussian curvature of polygon mesh was implemented in the Homologous Body Shape Model [4]. In contrast, our approach optimizes the generic model to multiple shapes of subjects. To avoid time-consuming process, we firstly prepare an original generic model that has a high density of vertices and apply it to sets of 3D data. Then we reduce the vertices from the original model by iteratively solving a representative selection problem based on the multiple shape data of the subjects.

A. 3D Body Measurements

3D measurements of 45 Japanese women ranged in age from 19 to 67 were taken by laser metrology in 1999 at Wacoal Corp. The average age of them is 32. Subjects were scanned in a naturally standing posture wearing only panties. The measurement data of the trunk of one subject consist of approximately 180,000 of 3D points. Each measurement point is transformed to cylindrical $u, v$ coordinates necessary in the fitting process (see APPENDIX). We classified the sets of the 3D data into two groups at random: 22 for analysis of vertex allocation, and 23 for allocation efficiency evaluation.

B. A Method of Vertex Allocation in Generic Model

(1) Creating Original Generic Model

Triangulating 60 x 50 vertices allocated to a square grid similar to that in Fig. 2 creates an original model. Fitting this model to the data for analysis by means of the least square method produces 22 sets of shape data. One set of shape data is composed of 60 x 50 = 3,000 vertices.

We have confirmed that the original model can express all of the 3D measurement data for analysis with satisfactory accuracy. The mean and the standard deviation of the average modeling errors of the 22 subjects were 0.75 and 0.07 mm. In addition, eighty percent of the measurement points could be reconstructed within the error of 1 mm, 19 percent with the error of 1 to 5 mm. Although the remaining 1 percent had the error of 5 to 49 mm, they were mostly found in cutting-planes between the arms from the trunk and a base curve of sagging breasts, and treating of them is beyond the scope of this study. Therefore, the original model can be judged as enough for the purpose of this study.

(2) Representative Vertex Selection

If a smaller number of vertices can be selected out of a huge number of those without losing shape information, then we can get a polygon model that satisfies the requirements (2) and (3) in Section I. We call such vertex selection as “representative vertex selection.” Our idea is that a certain vertex can represent the neighboring vertices if the vertex and the neighbors tend to form a flat surface.

The vertex selection problem is solved by using a UV vertex map. This map divides the UV plane into 60 x 50 cells. Each cell denotes one of the vertices. It clearly defines adjacent cells and, therefore, distance in $u$ and $v$ directions. The UV vertex map also enables us to visualize the result of the representative vertex selection as shown later in Fig. 3. Here we assume that a vertex can represent its neighboring vertex if they satisfy the two conditions: the neighbor is located within three cells in $u$ and $v$ directions from the vertex on the UV map; the neighbor is not more than 2.5 mm away from the plane defined by the position and the normal vector of the vertex in $\mathbb{R}^3$ space for any of the 22 subjects. These conditions are based on our experience. Then, the procedure to select the representative vertices is as follows.

1. For each cell on the UV vertex map, calculating the number of its neighboring vertices that the vertex in
question can represent.

2 Selecting the vertex that has the largest number as a representative.

3 Removing the cells of the representative vertex and the neighboring vertices that the vertex can represent.

Steps 1-3 were repeated until all of the cells are removed from the map.

Fig. 3. UV vertex map.
The black-cells are the 1,087 representative vertices. The gray solid lines surround the vertices that the representatives can explain.

C. Result of Vertex Allocation

As a result, 1,087 vertices shown in Fig. 3 were chosen as the representatives. Triangulating them provided a generic model that consists of 2,164 triangles. Fig. 4 depicts the triangulation of the generic model on the UV plane. Fig. 5 shows a comparison between the original generic model and the final one. The both generic models were fitted to the 3D data of the 22 subjects for analysis. Fig. 6 illustrates how many measurements can be reconstructed when a certain modeling error is tolerated, in percent figures (cover ratio). This demonstrates that the final model has similar accuracy if the error of 3 mm is tolerated. In what follows we use the final model as our generic polygon model.

Then this model was fitted to the 3D data of the 23 subjects for evaluation. Two of them are drawn in Fig. 7 as examples. The cover ratio for evaluation is also shown in Fig. 6. Statistics of the modeling errors is summarized in Table I.

Fig. 4. Triangulation of final generic model.
The three arrows indicate the cervicale, the left mamillae, and the umbilicus from the top.

Fig. 5. Original generic model (a) and finally given generic model (b) fitted to one of the subjects for analysis.

Fig. 6. Cover ratios of modeling errors for all measurements.

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IV. DISCUSSIONS

A. Isomorphism of Polygon Models

By introducing the UV plane and allocating polygon vertices to it, we could obtain the isomorphic generic polygon model. We can assume that the surface points having the same coordinate on the UV plane share the same bodily meaning, although they are on different individual models. For example the nipple point exists at the same position on the UV plane in any model. Thus given generic model can be fitted to 3D measurements by the least square method.

![Fig. 7. Examples of individual models](image)

Table I. Statistics of average errors [mm] in individual models.

<table>
<thead>
<tr>
<th></th>
<th>Analysis data</th>
<th>Evaluation data</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of subjects</td>
<td>22</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Mean error</td>
<td>1.16</td>
<td>1.19</td>
<td>0.37</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.10</td>
<td>0.14</td>
<td>0.047</td>
</tr>
<tr>
<td>Maximum error</td>
<td>1.48</td>
<td>1.49</td>
<td></td>
</tr>
<tr>
<td>Minimum error</td>
<td>1.04</td>
<td>0.98</td>
<td></td>
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B. Polygon Vertex Allocation

The vertex allocation reduced the number of vertices without losing the usefulness of the generic model. The original generic model had the average error of 0.75 ± 0.07 mm as mentioned in Section III B(1), and the final model had 1.19 ± 0.14 mm for the 22 subjects (Table I). Although the mean error of the final model is higher than the original by approximately 0.44 mm, it is sufficient to express shape of the human body. The increase in the error mainly occurred in the measurements that had the error within 3 mm before allocation (Fig. 6). And the difference of the cover ratio of the both models at the modeling error of 5 mm is only 0.37%. This results in a similarity of the models' appearance (Fig. 5). Therefore, we can utilize the new model as our generic polygon model.

The number of the vertices in the final generic model, 1,087, is sufficiently small and can be used for analyzing body shapes with a variety of statistical approaches. The compressibility ratio from the 3D measurements to the shape data is approximately 99.4%.

The vertices of the generic model tended to concentrate around the breasts and the groins in the UV plane (see Fig. 3 and Fig. 4). This phenomenon reflects complicated women's body shape. Moreover the density of the vertices was high around the neck and the waist (see Fig. 5(b)) because their surface areas in $\mathbb{R}^3$ space are relatively small compared to those on the UV plane. On the other hand, a certain number of the vertices were allocated to the cutting-planes between the trunk and the arms. The vertices on the cutting-planes should be eliminated in the future.

In order to compare the generic model with a model optimized to average body shape, we created a model consists of 1,099 vertices from the average shape of the 22 subjects for analysis using the polygon allocation procedure. The mean and the standard deviation of the average modeling errors of the 23 subjects for evaluation were 1.26 and 0.14 mm. This result demonstrates that the generic model that was derived based on the multiple sets of the 3D data is more accurate than the model derived from the average shape. The former with a smaller number of vertices reduced the modeling error by approximately 5.3% from the latter.

The finally given generic model was symmetrical in allocation of the vertices as seen in Figs. 3 and 4, but its symmetry was not complete. The generic model can be symmetric by devising the vertex allocation and triangulating processes.

C. Modeling Accuracy

The experimental results showed that the generic model can describe the trunk shape accurately with a small number of parameters. In Table I and Fig. 6, there is no significant difference between the models for analysis and for evaluation. Although the number of subjects for analysis in this study was small, the generic model is more likely to be applicable to a majority of Japanese women except for those having largely sagging breasts because of their difficulty to be measured by a laser scanner.

The mean of the average errors for evaluation was 1.19 mm. Even the model having the maximum modeling error, 1.49 mm, had sufficient accuracy for practical use.

V. CONCLUSION

In this paper, the authors have presented the trunk shape model that combines the features of the B-spline model [9], [10] suitable for statistical analysis and polygonal mesh easy to manipulate. Initially we have proposed the method to describe a point on polygon mesh by the linear combination of the vertices in $\mathbb{R}^3$ space and their internal division ratios on the UV plane. This enables us to control polygon mesh on the UV
plane. Also the least square fitting of the polygon model frees us from the restrictions of the FFD.

Secondary we have proposed the method to allocate polygon vertices of the isomorphic polygon model in order to explain the trunk shape efficiently and accurately. The vertex allocation has been achieved through the shape analysis based on the multiple sets of the shape data. The derived generic model was applied to the data for evaluation. The generic model consists of 1,087 vertices and 2,164 triangles and can reconstruct the original shape with the average error of 1.19 ± 0.14 mm.

The authors are planning to extend the mechanism of the UV plane to the whole body and to improve the model to describe the shape of sagging breast.

APPENDIX: DERIVATION OF UV PLANE

Here we briefly explain the mapping of 3D measurements of the trunk onto the UV plane normalized by the 17 anatomical feature points. The mapping is done via an RS plane. The RS plane is a cylindrical surface having the circumferential and height coordinates. A set of 3D measurements is mapped onto this plane based on a pseudoaxis within the trunk. The 17 feature points including the acromions, the nipple and the iliospinales on the body surface are also projected on the RS plane. Fig. A(a) shows an example of the plane. It is triangulated using the feature points and the 23 auxiliary feature points derived through geometrical operation on the feature points. The dots in the figure show the feature points. Obviously, configuration of the RS plane, feature point positions and triangle shapes, differs subject-by-subject reflecting their body shapes.

Then the RS plane is transformed into the UV plane. The UV plane is normalized by means of the feature points: they have their own predetermined coordinate as described in Section II. Its configuration, therefore, is common among subjects as shown in Fig. A(b). The transformation of the RS plane into the UV plane is linearly done triangle by triangle. As a result, all the measurements have their own \( u \), \( v \) coordinates on the UV plane. Via the \( u \), \( v \) coordinates B-spline body shape models are isomorphic.

![Fig. A. RS plane (a) and UV plane (b).](image)

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REFERENCES