A CAD System for Evaluating Footwear Fit

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Abstract. With the great growth in footwear demand, the footwear manufacturing industry, for achieving commercial success, must be able to provide the footwear that fulfills consumer's requirement better than it's competitors. Accurate fitting for shoes is an important factor in comfort and functionality. Footwear fitter measurement have been using manual measurement for a long time, but the development of 3D acquisition devices and the advent of powerful 3D visualization and modeling techniques, automatically analyzing, searching and interpretation of the models have now made automatic determination of different foot dimensions feasible. In this paper, we proposed an approach for finding footwear fit within the shoe last data base. We first properly aligned the 3D models using "Weighted" Principle Component Analysis (WPCA). After solving the alignment problem we used an efficient algorithm for cutting the 3D model in order to find the footwear fit from shoe last data base.

Keywords: 3D acquisition, Alignment, "Weighted" Principle Components Analysis.

1 Introduction

Footwear fit is one of the most important consumer considerations when purchasing shoes. Properly constructed footwear may provide the right pressure and force at the different locations on the foot surface, and this may result in improved comfort, fit and foot health. The design of new shoes starts with the design of the new shoe last. A shoe last is a wooden or metal model of human foot on which shoes are shaped. Traditional foot measurement techniques took a lot of time and custom-tailored shoe making has to make a great deal of work for each specific consumer, i.e. specific consumer's foot and shoe last must be manually manufactured with shoe maker's experience.

Customer's focus can influence today's business. Mass customization starts with understanding individual customer's requirements and it finishes with fulfillment process of satisfying the target customer with near mass production efficiency. The issue of good shoe fit was posed as early as 1500 B.C. in " Ebers Papyrus", which describes a wide range of illnesses from poor footwear. Well designed of shoe last, which represent the approximate shape of the human foot, is very important in the

D. Ślęzak et al. (Eds.): MulGrab 2009, CCIS 60, pp. 1–7, 2009.

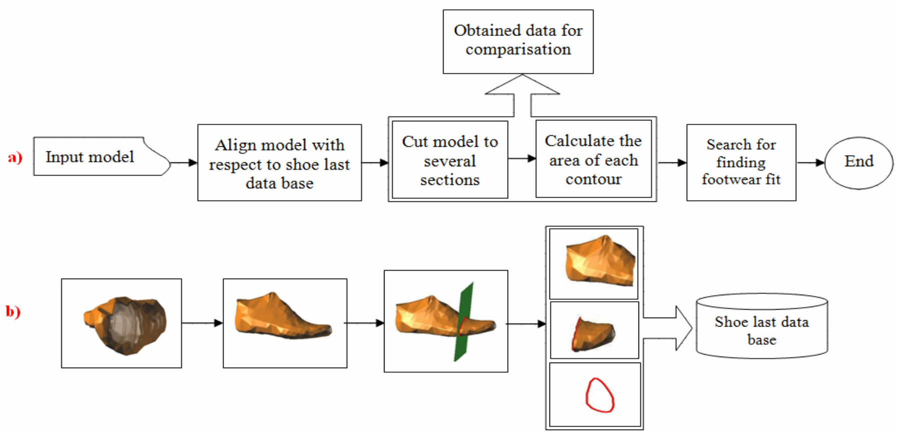

Fig. 1. a, b. Algorithm flowchart and its illustration. a) The flowchart. b) The illustration of flowchart.

whole shoemaking process. Traditionally, foot dimensions are measured using the device such as the Ritz Stick device [1], the Brannock device [2], the Scholl device [3], calliper and tape are used for measurement of foot dimensions. Foot measuring always takes a lot of time.

Unlike any other consumer product, personalized footwear or the matching of footwear to feet is not easy if delivery of comfortable shoe is to be the ultimate goal, even though footwear related discomfort is predominantly caused by localized pressure induced by a shoe that has a design unsuitable for the particular foot shape.

There are already some approaches in literature [4], [5] and [6]. The typical suggestion coming from literature is selecting a shoe last from a shoe last data base or deforming it into one that fits the scanned foot data. For instance, Li and Jneja [4], obtained the new shoe last by generating smooth surface between two given disjoined surfaces of the front and rear parts of the shoe last. This method is helpful for companies which already maintain library of shoe last rear parts. However, this method is not very accurate because the consumer's foot may change from time to time. Authors in [7], used colour-code mismatch between human foot and shoe last quantify footwear fit to predict the fit related comfort.

Nowadays, the combination of 3D scanning system with mathematical technique makes it possible, to produce shoe last automatically based on consumer's foot shape.A meaningful way to evaluate footwear compatibility would be to determine the dimensional difference between the foot and shoe. The approach proposed in this paper is meant to automatically align 3D models and cutting 3D model to several sections. Then the area of each section (available contours) is calculated and compared with the area of equal sections in shoe last data base. So that best fit can be obtained relatively automatically and quickly. Figure 1 shows the flowchart of our proposed process presented in this paper.

This paper is structured as flows: Section 2 presents alignment of 3D model, while in Section 3 we present an efficient algorithm for cutting the 3D model. Finally, the conclusion remarks are gathered in section 4.

2 Alignment of 3D Model

Point-clouds resulting from 3D scanning are given in an arbitrary position and orientation in 3D space. Pose estimation of a 3D-mesh model, based on the Extended Gaussian Images (EGIs) [8], is one of the first approaches reported in the literature. An EGI defines a function on a unit sphere, by using normal vectors of faces of the mesh. The method is sensitive to polygon tessellations of a 3D-shape, noise, and face orientation. Minovic et al. [9] introduce a method based on the computation of symmetries of a principle octree aligned with the principle axes.

Principle Component Analysis (PCA) is a common method extensively used in analysis, compression, neutral computing and recognition of objects because of its simplicity and ability for dimensionality reduction [10], [11]. The purpose of the principle component analysis applied to 3D model is to make the resulting shape feature vector independent to translation and rotation as much as possible. Comparing two models requires finding the rotation at which the models are optimally aligned.

We may apply PCA to sets of 3D point-clouds, but different sizes of triangle meshes cannot be considered. In order to account for different sizes of triangle Paquet et al. [12] established weights associated to center of gravity of triangles and Vranic et al. [13] used weighting factors associated to vertices. These two methods showed improvements if compared to the classical PCA. The "weighted" PCA analyses were designed to approximate the PCA of the whole point set of the model.

All the models should be aligned at equal position, in order to have equivalent cross sections from center of mass of each model towards the heel and toe. To achieve the alignment we described the main steps and details of "weighted" PCA in the next subsection. First, we applied Step 1 through Step 3 for the first model in shoe last data base (See Figure 2). Then, for alignment of another models with the first model we applied Steps 1, 2, 4, 5. (See Figure 3).

Let $T=\{t_1, \dots, t_n\}$ ($t_i \subset R_3$) be a set "triangle mesh", $V=\{v_1, \dots, v_n\}$ ($v_i = (x_i, y_i, z_i) \in R_3$) be a set of "vertices" associated to triangle mesh and c be the "center of gravity" of the model.

Step 1. Translate center of gravity to the origin and create a new list of vertices, I , such that:

$$c = \sum_{i=0}^{n} \frac{v_i}{n} \quad (1)$$

$$I=\{v_1-c, \dots, v_n-c\} \quad (2)$$

Step 2. Let A be the total sum of the areas of all triangles in the mesh, let A_k be the area of triangle k within the mesh, let ct_i be "center of gravity of each triangle " and ct

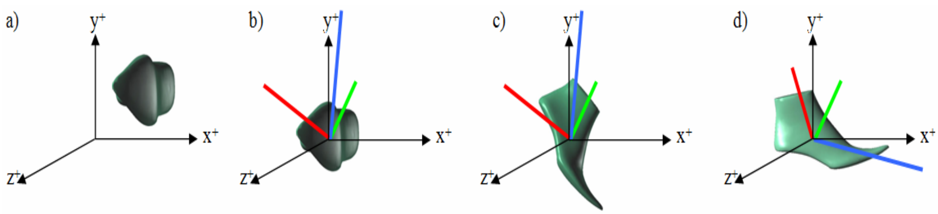

Fig. 2. a) Input 3D smooth triangle. b) Translated center of gravity to the origin. The red, green and blue lines are eigenvectors. c) Rotated 3D model with it's eigenvectors. d) Target model.

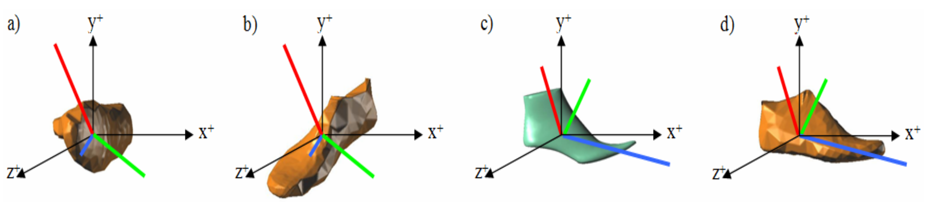

Fig. 3. a) Translated center of gravity to the origin. b) Rotated 3D foot model. d) The alignment of 3D foot in b with shoe last in c.

the total sum of "center of gravity" of all of triangles in mesh. The covariance matrix (3*3) is determined by:

$$ct=\sum_{i=0}^{n}\frac{ct_i}{n}(ct=(x_i,y_i,z_i\in R_3)) \tag{3}$$

$$CM=\begin{bmatrix} \mathrm{cov}_{xx} & \mathrm{cov}_{xy} & \mathrm{cov}_{xz} \\ \mathrm{cov}_{yx} & \mathrm{cov}_{yy} & \mathrm{cov}_{yz} \\ \mathrm{cov}_{zx} & \mathrm{cov}_{zy} & \mathrm{cov}_{zz} \end{bmatrix} \tag{4}$$

$$\mathrm{cov}_{xx}=\sum_{i=0}^{n}\frac{A_i(ct_i x-ctx)(ct_i x-ctx)}{A} \tag{5}$$

Covariance matrix CM is a symmetrical real matrix, therefore its eigenvectors are positive real numbers and orthogonal. We sort eigenvalues in decreasing order to find the corresponding eigenvectors and to scale them in Euclidean unit lengths.

The rotational matrix R is constructed with eigenvectors in rows. We apply this matrix to all of the vertices of a triangle and we form a new vertex sets called:

$$I'=\{R\times I_1,\ldots, R\times I_n\} \tag{6}$$

Step 3. Rotate first shoe last with its eigenvectors in Figure 2.c up to a position where the foot shape becomes parallel with x-y space, see Figure 2.d. Record the new position of these 3 eigenvectors in the file as the origin matrix, O_{em}.

$$O_{em}=\begin{bmatrix} OrgionEig_1x & OrgionEig_2x & OrgionEig_3x \\ OrgionEig_1y & OrgionEig_2y & OrgionEig_3y \\ OrgionEig_1z & OrgionEig_2z & OrgionEig_3z \end{bmatrix} \tag{7}$$

Step 4. Let matrix N_{em} be transpose of a matrix R and O_{em} be the origin matrix that is recorded in step 3. The alignment is accomplished by constructing a rotation matrix R' through the following formula:

$$R' = O_{em} \times N_{em} \tag{8}$$

Step 5. Get the matrix R' calculated in Step 4 and apply it to all I′. New point sets I'' are calculated .see Figure 3.

$$I' = \{ R' \times I_1', \ldots, R' \times I_n' \} \tag{9}$$

3 Cutting 3D Model into Several Sections

The similarity search algorithm is based on the cutting foot triangle mesh into several sections towards the heel and the toe. Then the area of each section (available contour) is calculated and compared with the area of equal sections in shoe last data base

Let M be the mesh structure of the model. A triangular mesh is defined as a set of vertices and a set of edges and triangles that join these vertices. The two triangles which share a common edge are called adjacent triangles. The model consists of three list V, E, T as follows:

Triangle list consists of 3 edges, edges list consists of 2 vertices and adjacent triangles and Vertex list consists of coordinates in 3D ($v_i= (x_i, y_i, z_i) \in R_3$). Fig.4.a is illustrated these basic concepts.

3.1 Search for Similarity Estimation

The algorithm has the following steps summarized in Figure 4.b. First, find the intersection of the cutting plane with the edge of a triangle and create new vertex. Then, choose the edge with the endpoints on the opposite sides of the intersection point and build edge between the intersection point and the opposite vertices of the current edge's triangles. Next, build new triangles between the new edges. Finally, Update the triangles and vertices of the current edge and add new triangles and the edges to the list.

The output of our algorithm is a set of vertices and edges related to each contour . Let Vc $=\{v_1, \ldots, v_n\}$ ($v_i= (x_i, y_i, z_i) \in R_3$) be a set of "vertices" and $E_c=\{e_1, \ldots, e_n\}$ the set of "edges" associated to the contours. The area of each contour can be calculated by finding center of contour (c_{oc}) and dividing the vertices of contour's edge and center of contour in triangles. Let A_i be the area of each associated triangle in the contour and N be the number of triangles that associated with the edges and center of gravity of contour. The area of each contour can be calculated as follow:

$$c_{oc} = \sum_{i=0}^{n} \frac{Vc_i}{n} (c_{oc} = (x_i, y_i, z_i \in R_3)) \tag{10}$$

$$A = \sum_{i=0}^{N} A_i \tag{11}$$

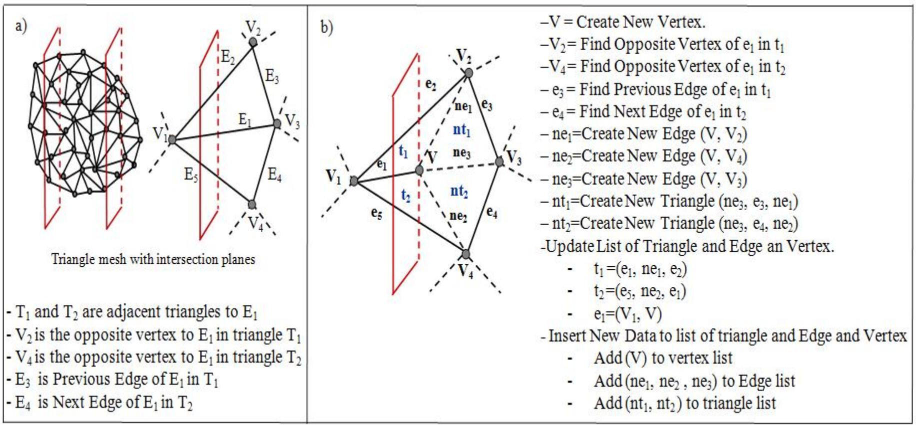

Fig. 4. a) Basic concepts related to algorithm. b) Steps for cutting shape to several.

4 Conclusion

In this paper, an approach for computerize footwear fit is proposed. It deals with the alignment of foot with shoe last data base and an efficient and precise algorithm for cutting the model to several sections to find the footwear fit within a shoe last data base. This approach should clearly help to improve the user's comfort and it could be the starting point for mass customization approach in footwear design. As a future work and development, the specific sections of the foot will be compared to corresponding sections of shoe last data base, so that new shoe lasts will be designed in such a way that they fit costumer's feet completely.

References

1. Ritz (2006), `http://www.ritzstick.com/`
2. Brannock (2006), `http://www.brannock.com/`
3. Hawes, M.R., Sovak, D.: Quantitative morphology of the human foot in a North American population. Ergonomics 37, 1213–1226 (1994)
4. Li, G., Jneja, A.: A Morphing-Based Surface Blending Operator for Footwear CAD. In: Proceedings of the International Mechanical Engineering Congress and Exposition (2004)
5. Mochimaru, M., Kouchi, M., Dohi, M.: Analysis of 3D human foot forms using the Free Form deformation method and its a application in grading shoe lasts. Ergonomics 43(9), 1301–1313 (2000)
6. Kim, S.Y., Lee, K., Hwang, T.: A grouping algorithm for custom-tailored products. Journal of Materials Processing Technology, 618–625 (2002)
7. Luximon, A., Goonetilleke, R.S., Tsui, K.L.: A Fit Metric for Footwear Customization. In: Proceedings of the World Congress on Mass Customization and Personalization, vol. 16 (2001)
8. Kang, S.B., Ikeuchi, K.: 3D object Pose Determination Using Complex EGI. Tech. Rep. CMU-RI-TR-90-18, The Robotics Institute, Carnegie Mellon University (1990)

9. Minovic, P., Ishikawa, S., Kato, K.: Symmetry identification of a 3-D object represented by octree. IEEE Trans. Pattern Anal. 15 (1993)
10. Bustos, B., Keim, D., Saupe, D., Schreck, T., Vranic, D.: An Experimental Comparison of Feature-Based 3D retrieval Methods. In: 3DPVT 2004, Thessaloniki, Greece (2004)
11. Paquet, E., Rioux, M., Murching, A., Naveen, T., Tabatabai, A.: Description of shape information for 2-D and 3-D objects. Signal Processing: Image Communication 16 (2000)
12. Paquet, E., Rioux, M.: Nefertiti: a query by content system for three-dimensional model and image databases management. Image and Vision Computing 17, 157–166 (1999)
13. Vranic, D., Saup, D.: 3D Model Retrieval. In: Proc. SCCG (2000)