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# Mass Customization Strategy In Footwear Industry

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*Abstract*— **At this point of time, one of the trendy key word in the clothing industry all over the world especially for footwear industry is "Mass Customization". Thus shoe making manufacturers to survive and to be successful within an increasingly globalish market they need to fight competition on different grounds such as flexible automation and IT solution that enable high variance in operation at low switching cost. Footwear fitter measurement have been using manual measurement for a long time. Along with the development of 3D acquisition devices and the advent of powerful 3D visualization and modeling techniques, automatically analyzing have now made automatic collection of consumer foot data for further analysis such as shoe last design and population distribution as well as for communication with customers for determining footwear fit. Data resulting from 3D scanning are given in arbitrary positions and orientations in space. To apply sophisticated modeling operation on these data sets, substantial post-processing is usually required. For alignment of the foot with shoe last data base we apply weighted principle component analysis. Then in order to produce the right fit and comfort, we estimate longitudinal shoe last curvature with concentrated curvature method based on customer's foot.**

***Keywords*—Mass customization, shoe last, weighted principle components analysis, concentrated curvature**

## I. Introduction

Research indicates that customer focus can influence today's business. Footwear fit is one of the most important consumer considerations when purchasing shoes. Thus, one of the main trends in today's market is that of mass customization which represents a new market paradigm that is changing the way consumer products are designed, manufactured, delivered and recycled. 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. This is certainly true for shoe production; as footwear manufacturing is increasingly confronted with different production batches which are faced with different customer's need. However, since a noticeable demand for such products is becoming evident among shoe consumers, footwear companies will soon have to confront these kinds of technical challenges. Such new paradigm need increasing flexibility in manufacturing systems and high speed of information exchange [1] [2].

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Very few standards exist for fitting products to people. Footwear fit is a noteworthy example for consumer considerations when purchasing shoes. The dynamic world of footwear is neither an easy task to produce neither a simple business. Because the foot has soft, deformable parts and it has a complex 3D shape. Thus the quality of the user's foot adaption, which has a decisive influence on the functionality and comfort of the product is not simple and true custom footwear is expensive to produce because of the complexity and the constraints imposed by footwear manufacturing process.

Rapid design and production technique are indispensable in areas of footwear industry where in past the design and manufacturing of such products relied on manual processes such as the Ritz Stick device [3], the Brannock device [4], the Scholl device [5], calliper and tape or on the accumulated experience of skilled craftsmen. In such industry, the shoe last which is a mechanical form is made from various material, including hardwoods, cast iron and high density plastic should be designed rapidly from the individual foot model.

As the 3D non-contact optical scanner has become a fast and convenient way of collecting surface data. In such system shoe last can be scanned in the same way as feet and stored in the shoe last data base for further analysis such as shoe last design and population distribution as well as for communication with customers.

An approach to computerize footwear fit is proposed in this paper. As 3D models are generally given in arbitrary scale, position and orientation in 3D-space. In order to perform sophisticated modeling operation on these data sets, substantial post-processing is usually required before taking geometric model in manufacturing design process. Thus, at first 3D foot model should be aligned with shoe last data base from heel to toe. When all the models are aligned, the longitudinal shoe-last curvature or so called "flare" and is one of the critical design feature for a shoe since it has to be compatible with the wearer's foot curvature in order to produce the right fit and comfort should be estimated. In such system shoe last flare is estimated and stored in the shoe last data bases. Then the curvature of 3D customer's foot is estimated in the same way and searched in shoe last data base for finding similar curvature and evaluating footwear fit.

In summary, the problem of finding the best fitting shoe within a given shoe last data base, using input data taken from the 3D foot scan of client consists of two main sub problem:

- Alignment of 3D foot with shoe last data base.
- Estimation of flare for evaluating footwear fit.

The remainder of this paper is structured as follows: Alignment of 3D foot and shoe last which is based on the weighted principle component analysis is described in section II, while in section III a method for estimation curvature is presented. Finally, conclusions are given in Section IV.

## II. Alignment Of 3D Foot Model With Shoe Last Data Base

The problem of 3D model's alignment is well studied and it used in many application of computer graphics, such as visualization, 3D object recognition, 3D shape matching and retrieval [6-8] is an important step in the normalization process. Thus, 3D foot model must be properly positioned and aligned before shape analyses such as determining the curvature of foot for finding the shoe last in data base which satisfies the such customer's need.

One of the first approaches reported in the literature for pose estimation of 3D model is Gaussian Images (EGIs) [9] which is based on defining a function on a unit sphere, by using normal vectors of faces of the mesh. Another approach is based on the computation of symmetries of a principle octree aligned with the principle axes [10]. A probabilistic model [11] is proposed where a Gaussian mixture with centroids corresponding to the first set is fit to the second point set by maximizing the likelihood, while in [12], both point sets are represented as a Gaussian mixture model and then the L2 distance of the two mixtures is minimized. Principle Component Analysis (PCA) also called Karhunen-Loeve transform or Hotelling transform is a method that has been extensively used for analysis, neural computing, modeling and recognition. Reel et al. [13] applied this method for aligning models. This method aligns models by considering its center of mass as the coordinate system origin, and its principle axes as the coordinate axes. 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. In analysis, instead of applying the PCA in classical way (sets of 3D point-clouds), in order to account different size of triangle weighted principle component analysis(WPCA) is used [14].

To achieve the alignment we describe the main steps and details of WPCA in the next steps. First, we apply step 1 through step 6 for the first model in shoe last data base, (see Figure 1). Then, for alignment of another models with the first model we apply step 1 through step 5 and steps 7 and 8, (see Figure 2).

Let T={$t_1$ ,….,$t_n$ } $(t_i \subset R^3)$ be a set of "triangle mesh" and V={$v_1$,…,$v_n$}($v_i$=( $x_i$, $y_i$, $z_i$)) be a set of "vertices" associated to triangle mesh, matrix $OM_E$ be **O**rigin **M**atrix of **E**igenvectors that is included the position of eigenvectors of shoe last as column, $P_c$ be the "barycenter of a foot model", A be the total sum of the areas of all triangles in the mesh, $A_i$ be the area of triangle i within the mesh, $T_{ci}$ be "barycenter of each triangle" and $T_c$ the total sum of "barycenter of each triangle" of all of triangles in mesh. The main steps of WPCA is described the following steps:

**Step 1.** Accomplish the translation invariance by finding the barycenter of the model as follow

$$x_c = \frac{1}{n}\sum_{i=0}^{n} x_i \qquad y_c = \frac{1}{n}\sum_{i=0}^{n} y_i \qquad z_c = \frac{1}{n}\sum_{i=0}^{n} z_i \tag{1}$$

**Step 2.** Move $P_c$ to coordinate origin.

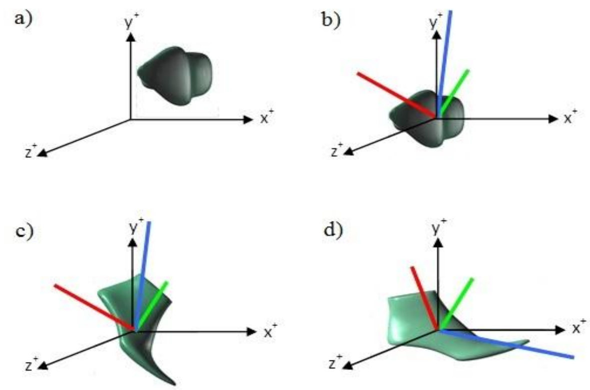


Figure 1. a) Input 3D smooth triangle. b) Translated barycenter of the 3D model to the origin. The red, green and blue lines are eigenvectors. c) Rotated 3D model with it's eigenvectors. d) Target 3D model

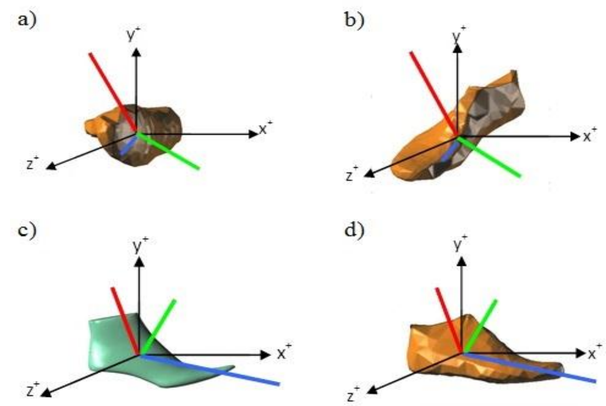


Figure 2. a) Translated barycenter to the origin. b) Rotated 3D foot model. d) The alignment of 3D foot in b with shoe last in c

That is to say, for each coordinate of vertex $v_i$, a corresponding transformation $v_i' = \{x_i - x_c, y_i - y_c, z_i - z_c\}$ is performed and define new vertex set $v' = \{v_1', v_2', \dots, v_n'\}$.

**Step 3.** Calculate the **C**ovariance **M**atrix $C_M$ type(3×3)

$$C_M = \begin{bmatrix} Cov_{xx} & Cov_{xy} & Cov_{xz} \\ Cov_{yx} & Cov_{yy} & Cov_{yz} \\ Cov_{zx} & Cov_{zy} & Cov_{zz} \end{bmatrix} \tag{2}$$

Where

$$T_c = \frac{\sum_{i=0}^{n} Tc_i}{n} \tag{3}$$

$$Cov_{xx} = \frac{\sum_{i=0}^{n} A_i (T_{ci}x - T_c x)(T_{ci}x - T_c x)}{A} \tag{4}$$

Obviously the matrix $C_M$ is a symmetric real matrix, there for its eigenvalues are non negative real numbers and orthogonal.

**Step 4.** Sort the eigenvectors in a decreasing order and find the corresponding eigenvectors. The eigenvectors are scaled to Euclidean unit length and form the rotation matrix R which has scaled eigenvectors as rows.

**Step 5.** Apply matrix R to all of the vertices of a triangle and form a new vertex sets called:

$$v'' = \{R \times v_1', \dots, R \times v_n'\} \tag{5}$$

**Step 6.** Rotate first shoe last with its eigenvectors in Figure 1.c up to a position where the foot shape becomes parallel with x-y space, (see Figure 1.d). Record the new position of these 3 eigenvectors in the file as the origin matrix, $OM_E$.

$$OM_E = \begin{bmatrix} OrigionEigx & OrigionEigx & OrigionEigx \\ OrigionEigy & OrigionEigy & OrigionEigy \\ OrigionEigz & OrigionEigz & OrigionEigz \end{bmatrix} \quad (6)$$

**Step 7.** The **T**ranspose of a **M**atrix R be TM. The alignement is accomplished by constructing a rotation matrix $R'$ through the following formula:

$$R' = OM_E \times TM \quad (7)$$

**Step 8.** Get the matrix $R'$and apply it to all $v''$and calulate new vertex sets $V_A$ as the alignment of the model

$$V_A = \{R' \times v''_1, \ldots, R' \times v''_n\} \quad (8)$$

# III. Curvature Estimation On Triangulated Surface

To obtain the competitive advantages promised by the mass customization paradigm which embrace both a closer reaction to the customer's needs and efficiency with innovative manufacturing processes, estimation of "flare" which is one of factor for evaluating footwear fit in industry is necessary, (see Figure 3).

Figure 3. Flare is curvature of Bottom parts of the foot and shoe last

A variety of techniques have been proposed to estimate curvature on triangle meshes[15]. Meyer et al. [16] are approximated important geometric attributes, including normal vector and curvatures for piecewise linear surfaces such as arbitrary triangle meshes. They defined the first and second order differential attributes such as normal vector n, mean curvature $K_H$, Gaussian cuvature $K_G$, principal curvatures $K_1$ and $K_2$ and principal directions $e_1$ and $e_2$. To extend the continuous definition to the discrete setting, the local spatial average of these attributes over the immediate 1-ring neighborhood are determined. Then they introduced a formal derivation of these quantities for triangle meshes using the mixed Finite-Element/Finite-Volume paradigm.

Authors in [17], are applied a cubic-order approximation method which shows variation of quadratic fitting method for the approximation of curvature. In current method to create third degree terms in the least-squares solution for surface fitting, neighboring points and corresponding normal vectors at adjacent vertices are used. Cazals and Pouget [18] are introduced the method which is consists of fitting the local representaion of the mainfold a jet, and either interpolation or approximation. A jet is a truncated Taylor expansion, and the incentive for using jets is that they encode all local geometric quantities such as normal, curvatures, extrema of curvature, while Razdan and Bae [19] introduced a method which is based on biquadratic Bezier patches as a local surface fitting technique for determining curvature, where it used for approximation of the neighborhood of mesh vertex for computation of curvature instead of taking the quadric analytical function approach.

Grinspun et al. [20] applied a simple shape operator formulation, using normals as degrees of freedom. They have observed that normals are represented in a natural way as scalars of edges, similar to 1-forms. In the case of quasi-isometric surface deformations, their shape operator can serve as a starting point for formulating a quadratic bending energy.

Authors in [21] presented statistics approach for estimation curvature. The applied an algorithm which is capable of achieving an estimate of the curvature tensor by fitting a linear model to the normal variation samples in appropriately varying region around each point.

Zhihong et al. [22] presented a method based on converting each planer triangular facet into a curved patch using the vertex positions and the normal of three vertices of each triangle and calculation the per triangle curvature of the neighboring of a mesh point.

Considering estimation of curvature of flare, Mesmoudi et al. [23] proposed a technique based on concentrated curvature quite similar to ours which further will be used to estimate Gaussian, mean and principal curvature. A discrete version of Gauss-Bonnet theorem is satisfied by concentrated curvature and is used as an important tool for analyzing attributes of triangulated surface. Unlike other methods in literature [24] [25], current method does not suffer from convergence problems.

## A. *Prelimiaries*

In computer graphics, curvatures are a fundamental property which plays a crucial role to understand the geometry and the topology of a surface. The curvature of a curve is the measure of its deviation from a straight line in a neighborhood of a given point, and the curvature becomes greater as this deviation becomes greater [26], (see Figure 4.a).

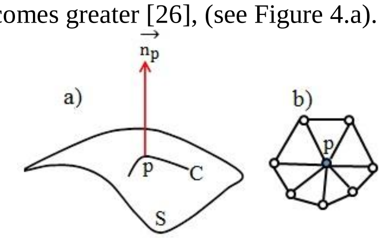


Figure 4: a)The view of curvature. b)Triangle incident in p

Let S be a surface, C be a curve in three dimensional Euclidean space, $\Sigma$ be a triangulated surface, p be a vertex of $\Sigma$, $\vec{n}_p$ be the normal vector at p which is defined by the average of the normal vectors of all the 1-ring triangles at a point p, (see Figure 4.b.), $\prod$ be a plane passing by p which contains the normal vector $\vec{n}_p$ and it cuts surface $\sum$ along the polygonal curve $C = \sum \cap \prod$, and $C_1$ and $C_2$ be corresponding curves which are orthogonal at point p [26].

**Euler's theorem:**

The Gaussian curvature K(p) and the mean curvature H(p) at point p are determined by

$$k(p) = k_1(p) \times k_2(p) \quad (9)$$

$$H(p) = \frac{1}{2\pi}\int_0^{2\pi} k(p)d\theta = \frac{K_1(p)+K_2(p)}{2} \quad (10)$$

**Gauss-Bonnet Theorem:**

Suppose $\chi$ be Eular characteristics of surface S(i.e., $\chi = 2(1-g)$), g be the genus of the surface and $k_g$ be the geodesic curvature at the boundary points(i.e., geodesic curvature is the norm of the projection of the normal vector of the curve on the tangent plane to the surface). For a compact surface S with a possible boundary component $\partial s$ we have

$$\iint_s K(p)ds + \int_{\partial s} k_g(p)dl = 2\pi\chi(S) \quad (11)$$

Note, a significant property of Gaussian curvature is given by the Gauss-Bonnet Theorem which relates the geometry of a surface, given by the Gaussian curvature, to it's topology, given by it's Euler characteristic .

## B. Concentrated Curvature For polygonal curve

In this section, concentrated curvature for polygonal curves is defined and it is used to define normal, principal, Gaussian and mean concentrated curvatures for a triangulated surface.

Let us suppose a and b be two neighbors of p on C, (see Figure 5.a,b), respectively, $\prod$ be a plane which is defined with a, b and p, $S_r \subset \prod$ be a circle of any radius r > 0 tangent C at two points $u \in [p,a]$ and $v \in [p,b]$, (uv) be the arc of $S_r$ which is bounded with u, v and located in triangle $\Delta(upv)$ and O be the center of $S_r$ and $\theta$ be the angle of $\angle uOp = \angle vOp$.

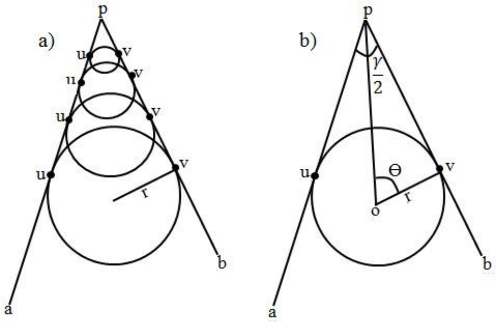


Figure 5: In (a), circles tangent to the sector from it interior. In (b), computing total curvature of arc (uv)

When angle $\gamma = \angle apb = \pi$ , thus the curvature value k(p) of C is 0. Otherwise the path [au] $\cup$(uv) $\cup$[vb] are used for specification the polygonal path apb for any value of r. The curvature value at any point of circle $S_r$ is constant and equal to $\frac{1}{r}$ . Thus the total curvature of (uv) is determined by

$$k = \int_{(uv)} \frac{1}{r}dl = \frac{1}{r}(uv) = \frac{1}{2}2r\theta = \pi - \gamma \quad (12)$$

Since quantity $\pi - \gamma$ depends only on the fracture angle $\gamma$, thus it is an intrinsic quantity of curve C at vertex p and it does not depend on the radius of circle $S_r$ through the curve is approximated. Finally, Concentrated curvature $k_C(p)$ of C at vertex p is the total curvature $\pi - \gamma$ of the arcs(uv) approximating curve C around point p which will be used in next section.

## C. Concentrated curvature for Triangulated 3D Surfaces

Note that the position of the normal vector $\vec{n}_p$ with respect to the polygonal curve C should be considered. Since the angle $\gamma$ of C at p is smaller than $\pi$ and the concentrated curvature value $\pi - \gamma$ is positive when the normal vector $\vec{n}_p$ and the polygonal curve C lie on two different half planes, (see Figure 6), otherwise, the angle $\gamma$ of C at p is larger than $\pi$ and concentrated curvature values which are bounded by two external values $k_{C,1}(p) \le k_{C,2}(p)$ are established when plane $\prod$ turns around $\vec{n}_p$. So that values $k_{C,1}(p)$ and $k_{C,2}(p)$ are matched to principal curvature and the positions of plane $\prod$ are matched to principal direction.

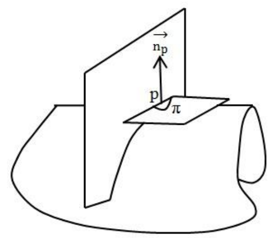


Figure 6: Intersection of plane $\prod$ with a smooth surface. Angle at p is divided into two equal angles

The Gaussian and mean concentrated curvature of surface $\Sigma$ are the vertex p are defined as product $k_{C,1}(p) \times k_{C,2}(p)$ and mean value of all normal concentrated curvature values which are obtained by turning plane $\prod$ around the normal vector.

Since the rotation of plane $\prod$ generate an infinite sequence of values, thus computation of all normal concentrated curvature values ($k_C(p)$) is impossible. For this aim, a discrete rotation around the normal vector $\vec{n}_p$ at a vertex p of the plane $\prod$ containing $\vec{n}_p$ is simulated by one plane for each vertex $v_i$ in the star of p. A polygonal line ($v_i p w_i$) is built, where $w_i$ is intersection point between plane $\prod_i$ and link of p. The angle $\gamma_i := \angle v_i p w_i$ , in the interior of the cone, between vectors $\overrightarrow{pv_i}$ and $\overrightarrow{pw_i}$ is determined by

$$\gamma_i = \arccos\left(\frac{\langle \overrightarrow{PV_i}, \overrightarrow{PW_i} \rangle}{pv_i \cdot pw_i}\right) \quad (13)$$

The normal concentrated curvature at p which is belong to polygonal line ($v_i p w_i$) is determined as $\mp(\pi - \gamma_i)$ where sign +1 or −1 is defined by following the position of the normal vector $\vec{n}_p$ with respect to the polygonal line ($v_i p w_i$). Following this construction, principal, mean and Gaussian concentrated curvatures can be defined at p.

# IV. Conclusion

An approach for evaluating footwear fit within the shoe last data base is proposed in this paper. This approach should clearly help to improve the users comfort and it could be the starting point for mass customization approaches in footwear design.

Data obtained by scanning 3D models typically are given in an arbitrary position and orientation in space. We applied the weighted principle component analysis technique for alignment of 3D foot with shoe last data base. When all the models are aligned, the flare of shoe-last which is one of the critical design feature for a shoe, since it has to be compatible with the wearer's foot curvature in order to produce the right fit and comfort, should be estimated and stored in shoe last data base. Then the curvature of 3D customer's foot is estimated and searched in shoe last data base for finding similar curvature and evaluating footwear fit. To this end, we suggested concentrated curvature to estimate curvature on a triangulated surface. As a future work and development, the specific sections of the foot will be compared and deformed with shoe last's data base, so that new shoe lasts will be designed in such a way that they fit costumer's feet completely.

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