A CAD Approach for Designing Customized Shoe Last

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ABSTRACT

This paper presents a novel CAD framework for designing customized shoe last. The new approach consists of two parts. The first part is a global deformation approach that can automatically form a customized shoe last based on a scanned foot data and an existing shoe last data. It uses the modified distant map method giving the design being similar to the last and fit with the foot shape. The second part is an interactive local deformation method. It allows the shoe last be modified in specific regions to meet various needs. Preliminary simulation results show that the new approach is effective.

Keywords: CAD, shoe last, distant map, local deformation, point cloud.

1. INTRODUCTION

Footwear is a must modern commodity. In 2004, for example, American consumer spending for athletic footwear amounts to $16.4 billion with an average price of $33.18 / pair [1]. With such a big demand, the competition in the shoe industry is also severe.

The style of the footwear is often the first element attracts the consumers. Next, the fitness is very important. Recent studies show that unfit shoes are the principal cause of forefoot disorder. In general, footwear is categorized by the length and the width. However, different consumers may have different foot shapes and have different requirements even though they may have same foot length and width. In order to find a pair of shoes that perfectly fit someone's feet, the measurement should to be more than just foot length and width [2] [3] [4]. Often, custom-tailored footwear is necessary.

Shoe last is a solid form around which a shoe is molded in the footwear making process. The fit of a shoe depends greatly on the shoe last [5]. During the design of the shoe last, one must consider the anatomical information of human foot and at the same time give the finished shoe a pleasing and fashionable appearance. The shoe last plays a crucial role in determining whether the footwear fits one's foot as well as the style of the footwear. To make well-fitted footwear, a well-designed custom tailored shoe last is required.

Traditional, making a custom tailored shoe last is expensive and time consuming because of the complexity and the constraints from the last design process. First, shoe last makers need to manually measure the customer's foot shape. Although it involves mainly 2D measurements, more than thirty measurements are required. Next, shoe last makers would have to make a wooden model manually, during which time, experience is very important. Furthermore, a number of trail-and-error modifications are often necessary.

In recent years, some research has been devoted to simplify the shoe last design process using the 3D laser scanner. Based on the 3D scanning, a complete foot shape data can be obtained. For example, Luximon [6] proposed to use a color coded mismatch between shoe last and human foot to quantify the footwear fit and predict the fit-related comfort. One suggested application of the proposed method is to choose a 'best-fitting' last from a group of available lasts. For this method, however, the details are not given and it is difficult to define what the 'best fitting' is. Li [7] suggested decomposing shoe lasts into the rear and the front parts and then using a morphing operator to joint the two different parts, as the front part is the part that contains the fashion factors. This gives more combination for the companies that already maintain a library of shoe lasts. Mochimaru [8] proposed to use Free Form Deformation (FFD) to change the shoe last shape by moving the control points around the shoe last. In this method, a last of width EE can be deformed from an existing last of width E. However, the deformation is not well constrained, it may change the original shoe last form, which contains the fashion or style factor. The aforementioned methods simplified the shoe last design process in some sense, but they were not applicable for custom tailored footwear design because they did not consider the fit between an individual's foot shape and the shoe last shape. Leng and Du [11] proposed a shoe last customization method based on a distance map and an amendment map. However, the amendment map is hard to be built and no local deformation was allowed in the method.

In this paper a customized shoe last design approach is proposed. It consists of two parts: The first part is a global shoe last design approach. It can automatically form a customized shoe last based on a scanned foot data and a scanned shoe last data, which uses the modified distant map method giving the design being similar to the last and fit with the foot shape. The second part is an interactive local deformation method. It allows the shoe last be modified locally to meet various needs.

The rest of this paper is organized as follows. Section 2 describes how to acquire the data from a 3D foot scanner and conduct pre-processing. Section 3 presents the automatic customized shoe last design method. Section 4 introduces the interactive local deformation technique. Section 5 shows a simulation result. Finally, Section 6 contains conclusions and future work.

2. DATA ACQUSITION AND PREPROSSING

The new approach is based on the 3D scanning of the foot shape data and the shoe last data. In this research, the foot shape data is acquired using a commercial foot scanner InFoot®, which consists of eight 1/4' progressive CCD cameras and four 670 nm semiconductor laser projectors. The scanned data is unstructured point cloud denoted as $P = \{p_i = (x_i, y_i, z_i) \mid 1 \le i \le n\}$. The scanning sample spacing is 1 *mm*. The data represents the underlying manifold surface. The shoe last data can be acquired in the same manner, as used in this research, but can also be obtained by digitizing the computer model of the shoe last.

Point cloud is an attractive primitive for rendering complex geometry. It has become a popular shape representation over the past few years. This is because, firstly, 3D scanning devices have become affordable and widely available. Also, point cloud is a good representation for complex geometry and easy to manipulate. The traditional way to use point cloud data is to reconstruct the underlying surface model represented by these points, for example as a triangle mesh or B-Spline surface. Though, when the size of the point cloud data is large, such methods may be rather computationally expensive. In this paper, we use the point cloud to represent the sampled surface directly. In other words, expensive surface reconstruction is not required.

Fig. 1(a) shows a scanned foot data. Note that as the individual stands on the scanner, the bottom of the foot appears to be flat. In reality, however, footwear always has a toe spring and heel height. Therefore, as shown in Fig. 1(b), in the pre-processing, the foot shape is adjusted to account for the toe-spring and hell height of the last. Note that the adjustment is based on the shape of the shoe last as shown in Fig. 1(c).

Also, the data acquired from scanning is usually disturbed by noises arising from various sources, such as measurement noise and sampling noise. Adaptive Moving Least Squares (AMLS) method [9] can be used as a smoothing filter to remove the possible noises.

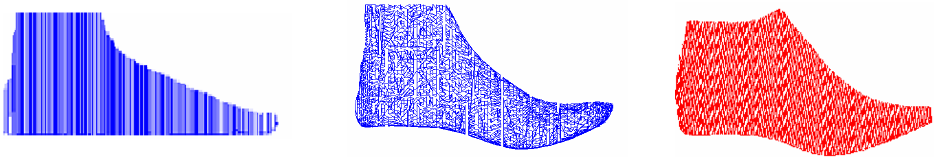

(a) (b) (c)

Fig. 1. (a) The original foot data; (b) The pre-processed foot data; (c) The scanned shoe last data.

3. AUTOMATIC DESIGN WITH GLOBAL DEFORMATION

To design a customer tailored shoe last, it is important that the shoe last represents the shape information of the customer's foot and at the same time, carries the fashion information of the chosen style. In the shoe industry, there already exists a lot of shoe lasts containing many different fashion styles. Hence, one can choose an existing shoe last as the base. Inevitably, the customer's foot will be different to the chosen shoe last. A distance map is calculated to indicate the difference between the shoe last and foot shape.

3.1 Distance Map Calculation

The distance map calculation takes the scanned foot data and the shoe last data as the inputs to calculate their difference. The first step is to estimate the normal vector of the two surfaces. For each point on the surface, the normal vector can be calculated based on its neighboring points [10]. The second step is to calculate the dimensional difference between the surfaces of the aligned foot and shoe last along the normal vectors.

The implementation procedure is as follows: First, the foot data and the shoe last data are aligned along the hell centerlines of the foot and last, which is the same as in [6]. Next, picking up the i^{th} data point of the shoe last, $1 \le i \le n$, the nearest foot data point can be found by searching along the normal direction (positive difference) or the opposite normal (negative difference). The distance d_i between the foot data point and shoe last data point is the dimensional difference. The distance map, D, is the collection of all the differences, which indicates the dimensional difference between the foot and the last.

Note that it is important to differentiate the positive and negative differences between the foot and last surface, as they have very different implications. Positive difference means the last surface is outside the boundary of the foot surface, which indicates the fit is loose; while the negative difference indicates the fit is tight.

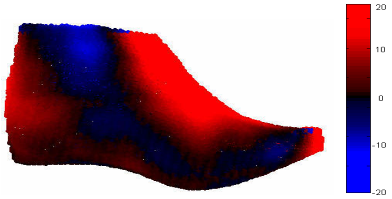


Fig. 2. The distance map calculated on the last surface, the unit of color bar is millimeter.

A sample distance map is shown in Fig. 2. The region in red shows the positive difference, while the region in blue shows the negative difference. We can see that the last is loose in the instep and heel seat part, while it is tight around the metatarsale tibiale, the netatarsale fiburale (the inboard and outboard of front part of the foot), and the ankle.

3.2 Distance Map Modification

To design a customized shoe last, simply deform an existing shoe last as close as possible to the foot shape is not sufficient. In fact, one must consider many constructive rules. For example, a positive difference is required in specific regions such as the instep and the toe regions to save space for the foot movement. On the other hand, for low cut shoe last as shown in Fig. 1(c), the shape around the ankle part contains no foot shape information and has no effect on the footwear fit, so it should remain unchanged during the customization. Moreover, while it is difficult to define a style, the features of a style are usually preserved in the front part of the shoe. Hence, to keep the original style of a selected shoe last, the simplest way is to preserve the shape of original last on the front part, especially the 'toe cap'.

With these considerations, the distance map, D, should be modified on some specific regions to account for the required regional differences. Let the modified distance map be referred as D'. The modification can be performed interactively. The user first selects the center of the region that needs to be modified, say, the j^{th} data point, d_j, and defines the expected difference around this point. To modify the selected region, different masks can be applied on the selected point and its neighborhood in the form of

$$d_j' = (d_j - d_{expected}) \cdot f(x) \tag{1}$$

where, $d_j \in D$, $d_j' \in D'$, x is the Euclidean distance from the center to the neighborhood of its boundary, and $f(x)$ is the mask function. A commonly used mask function is a Gaussian-like function given below:

$$f(x) = \exp\left(\frac{-x^2}{C}\right) \tag{2}$$

where, C is a constant. In our study, the modification is applied to three regions: toe cap, instep and ankle part.

Take the modification on the toe cap fro example. It is important to note there is a difference between foot length and shoe length (shoe last length), which is referred to as 'allowance' as shown in Fig. 3. This difference is used to save space for the foot movement inside the footwear.

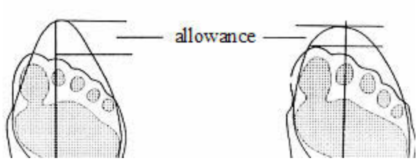


Fig. 3. The allowance and the toe design of shoe last.

There are different opinions on how much the allowance should be in proportion to the foot, but generally it shall be 12-15 *mm* depending of the shoe design. Fig. 3 shows a pointed toe design and a round toe design. Besides the appropriate allowance, the design of the toe cap should be preserved during the customization. With these two considerations, select the data point on the tip of shoe last, and apply the modification described in Equation (1), the result is shown in Fig. 4.

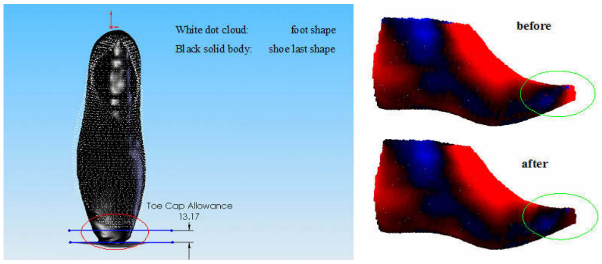


Fig. 4. The modification of distance map on the toe cap.

Other necessary modifications can be added based on aforementioned rules according to the experience of skilled last maker. Finally, an example of modified distance map is shown in Fig. 5.

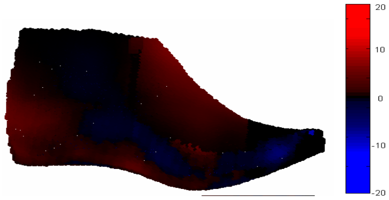


Fig. 5. The modified distance map.

3.3 Global Deformation

As shown in Figure 6, the customized design is performed on each sample point by deforming the original shoe last based on the modified distance map D'.

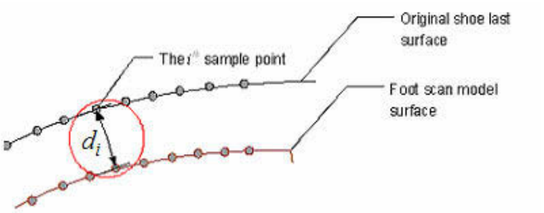


Fig. 6. Illustration of the difference d_i between last and foot surface on the i^{th} sample point.

Assume the i^{th} point of the shoe last is moved by a certain displacement, during the deformation. Such a displacement consists of two components. First, the last is slightly scaled in a whole by a coefficient, t_1:

$$\Delta x_i^1 = t_1 \cdot (p_i - p_0) \quad (3)$$

where, p_0 is the centroid of the shoe last. This movement changes the difference between the last and the foot in a whole without affecting the last shape. Second, we consider a deformation force, F_i, acted on the point drawing it towards a new position along the direction of its normal vector: $F_i = □ \cdot d_i'$, where, □ is a constant that converts the distance to the force. From a physical point of view, the displacement on a sample point under the force F causes the decrease of the difference between the foot and the last: $K(\Delta x_i^2) \cdot \Delta x_i^2 = F_i$, where, Δx_i^2 is the displacement produced on the i^{th} data point and K can be a simply a constant or a function of Δx.
Assume K is a constant, it follows that:

$$\Delta x_i^2 = t_2 \cdot d_i' \quad (4)$$

The variants t_1 and t_2 can be determined by minimizing the following objective function:

$$E = \beta \cdot \sum_i (P_i^{Foot} - P_i^{newlast})^2 + \sum_i (\Delta x_i^{\,2})^2 \quad (5)$$

where, the first term represents the difference between the foot and the new last shape; the second term indicates how much the shape of the new last is changed comparing to the original one. The coefficient □ controls the trade off between the last shape preservation and the fitting. This minimization problem can be solved by the Sum of Squared Differences (SSD) method [12]. This approach ensures that the new last can fit the custom's foot better while maintaining the minimal change to the original style of the base shoe last.

4. INTERACTIVE LOCAL DEFORMATIONS

From time to time, experienced shoe last designers may consider a shoe last inappropriate in specific locations. As a result, they may wish to make modifications manually. Note that the shoe last is represented by unstructured point cloud. Although many efforts have been put forward in developing shape controlling tools for designers [13] [14] [15] [16], a fast, convenient and intuitive method for point cloud free-form shape deformation remains to be a topic of research. In this research, an interactive local surface deformation technique is applied directly on the point cloud data. It requires no surface reconstruction but some inexpensive computation involving nearby points.

4.1 Basic Deformations

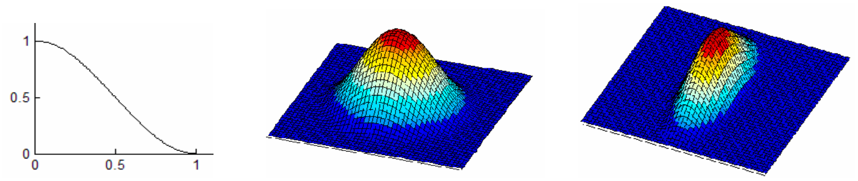
Since the shoe last surface is smooth, first, smooth deformations are required to keep this feature. Given an unstructured shoe last point cloud, an easy way to control the deformation is to specify some scattered points as control handle, and define a deformable region, called the Region Of Interest (ROI), that will be deformed with the movement of control handle on the surface. The user can then modify the surface by pushing or pulling this handle.
According to [13], if the ROI is precisely determined, the users' command can be translated into a continuous tensor field in the ROI. The tensor field is defined based on a continuously varying scale parameter $t \in [0, 1]$ that measures the relative distance of a point from the control handle in a rotational motion. The closer a point is to the handle, the stronger the deformation will be.
Suppose a point, p_j, is selected as the control handle and moved to a new position p_j'. The translation is

$$v = p_j' - p_j \quad (6)$$

Then, the other points in the ROI are modified based on the tensor field, t. It is rotated by a blending function f, as shown in Fig. 7(a), which is defined on the ratio of distance between a sample points p_i to the control point p_j and distance between the control point p_j to the boundary of ROI in p_i's direction. The resulting translation is:

$$P_i' = p_i + t \cdot v \quad (7)$$

Note that t may take various forms according to various ROI, as shown in Fig. 7(b) and (c). Also, $t(p_j) = 1$.
As shown in Equation (9), the deformation is controlled by the shape of ROI and the blending function.



(a) (b) (c)

Fig. 7. (a) The blending function, (b) Final surface with circular ROI, (c) Final surface with elliptical ROI.

In some cases, however, it is not convenient to give an exact ROI that can ensure the preservation of local shape properties during the deformation. Hence, in the subsequent section, an adaptive deformation technique is proposed.

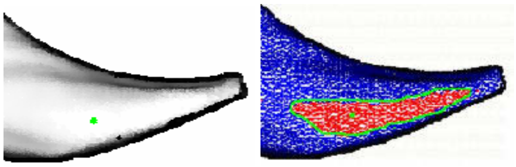
4.2 Adaptive Deformation

A major criterion in evaluating a surface editing technique is its ability to preserve the shape properties of the original model. Note that the shoe last surface is smooth. The preservation of local surface shape properties around the control handle during editing operations is of major significance. Hence, it is important that the local deformation is smooth and can adapt the local shape properties of the original surface.

Normal vectors are a set of vectors perpendicular to the shoe last surface; the direction of this vector represents the orientation of the surface. Obviously, the change of surface normal vectors around the control point contains information about the local shape properties of the control point neighborhood. Hence, we suggest an adaptive deformation method based on the normal vectors of the last surface. Let $N = \{n_i = (x_i, y_i, z_i) \mid 1 \leq i \leq n\}$ be the normal vectors of the last surface. Based on the basic deformation techniques described in Section 4.1, besides the distance, the surface normal change, $(1 - \langle n_i \cdot n_j \rangle)$, is also used to control the deformation. To preserve the local shape properties, the points with their normal vectors closer to the normal vector of the control handle point would be deformed more.

Suppose a point, p_j, is selected as the control handle and moved to a new position p_j'. The local shape property around this control point is studied based on its near neighbor. Fig. 8(a) shows an example: the control handle, p_j, is shown in green; Fig. 8(a) shows the normal change around the control point, where the whiter region indicates the surface normal is closer to that of p_j, and versa vise; Correspondingly, in Fig. 8(b), the region shown in red means that the normal change of all the sample points from the control point is less than three percent compared to p_j, that is, $\langle n_i \cdot n_j \rangle > a_1$, where $a_1 = 0.97$. The deformable region (ROI) is then has the shape of the local adaptive region shown in Fig. 8(b) indicated by the green spline. The extent of ROI can be controlled by a parameter a_2. The deformation will be:

$$p_i' = p_i + a_2 \cdot t \cdot v \tag{8}$$



(a) (b)

Fig. 8. (a) The normal change around p_j , (b) The shape of local deformation region.

5. A SIMULATION RESULT

The presented approach is implemented on a standard Microsoft Windows NT PC computer with a Pentium IV 3.06GHz CPU and 1G RAM. The software is written using Microsoft Visual C++ and can be used as a plug-in in the commercial CAD software system, SolidWorks®. As a result, all design / graphic tools of SolidWork® can be directly used and the design can be directly output to the CAM systems.

Using the foot and last data shown in Fig. 1, first the distance map is found as shown in Fig. 2. Next, the modified distance map is shown in Fig. 5. The modification to distance map may vary from time to time depending on the shoe last design. Using the method presented in Section 3, the global deformation result is shown in Fig. 9 and Fig. 10.

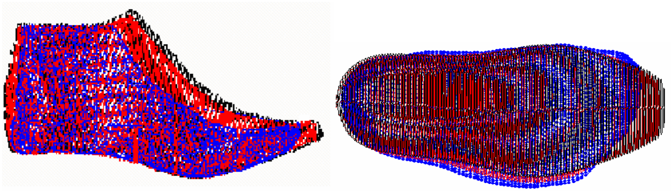
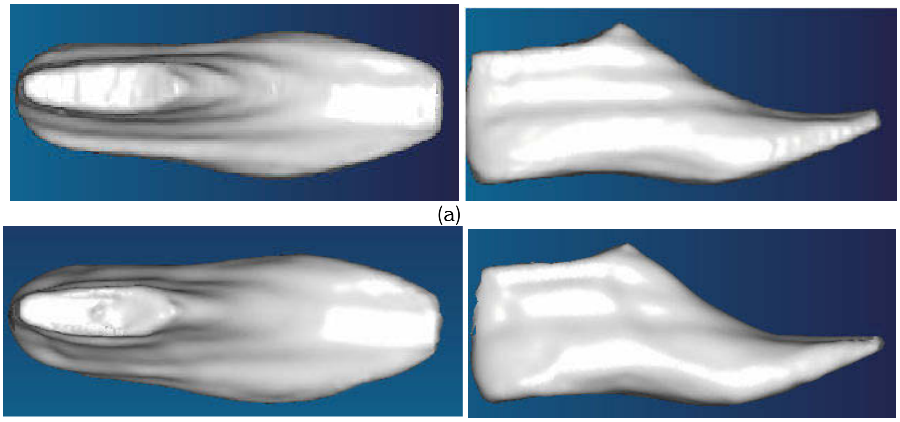


Fig. 9. The red one is the new last, the blue one is the foot and the black one is the original shoe last.

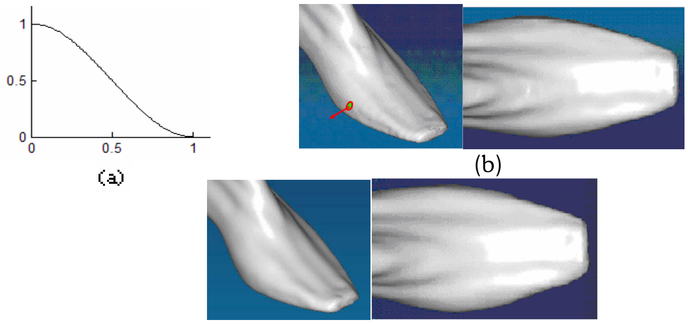
In Fig. 9, the foot shape data is shown in blue, the original last is shown in black, and the new last formed from global deformation is shown in red. From the figure, it is clearly that the new last fits the foot shape well. Also, from Fig. 10, it is seen that the new last preserves the style of the original last. From Fig. 12, we can see that the last style is well preserved.


(a)

(b)

Fig. 10. A comparison between (a) the original last and (b) the new last after global deformation.

Finally, assuming a local deformation is desired and the control handle is shown in Fig. 11(a), using the method present in Section 4, if the blending function shown in Fig. 11(a) is used with the control handle shown in Fig. 11(b), the deforming result is shown in Fig. 11(c).



(b)

(c)

Fig. 11. (a) The blending function, (b) Original surface, (c) Deformed surface.

6. CONCLUSIONS AND DISCUSSIONS

This paper presents a new CAD approach for designing customized shoe lasts. The new approach consists of two parts: the global deformation part and the local deformation part. The former merges a scanned foot data and an existing shoe last data to form a new last. As a result, it can automatically design a customized shoe last that fits the foot and at the same time maintains the basic features of the referred shoe last. The later deforms a specific region around a control handle. It can be used to fine tune the design to suit specific needs. A software system has been developed and can be run in the SolidWork® environment. The simulation result indicates that the new approach is effective.

We also found some limitations, which lead to the future research:

(a) In the global customization part, the deformation method introduced in Section 3.3 is straightforward but not very efficient in keeping the surface smooth during the deformation. It might helpful to incorporate techniques like AMLS [9] and differential coordinates [18] in the further improvement.

(b) In the local deformation part, the method works well on clear and simple surface like the shoe last surface. However, it is not applicable to surfaces with a lot of details. The deformation doesn't work in a detail preserving way.

(c) The presented method only derives a design that resembles the dimensional similarity of the foot and the selected shoe last. In practice, the comfort of a shoe is difficult to measure. It depends on a number of factors, which may be different from individual to individual. How to quantify the comfort of a shoe remains as an unsolved problem.

7. ACKNOWLEDGEMENT

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