A Deformation Method for Shoe Last Customization

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ABSTRACT

The production of custom tailored product is widely required in the manufacturing industry nowadays. This paper proposes a new method for designing custom shoe last. In this method, a consumer preferred last form is selected as the base form. By calculating the difference between the base form and scanned foot data from the consumer, a distance map is obtained to indicate how well the selected shoe last fits the specific foot shape and to guide the deformation. An amendment map is set up offline based on the experience information from experienced last maker to cater for last design regulations; it can also incorporate the function of preserving original last style by keeping the original last shape on specific regions such as 'toe cap'. The base last form is then deformed by minimizing the SSD of a designed equation, to fit the particular foot shape according to the distance map and amendment map, with the minimal change of the original last style. Preliminary experimental results are given to demonstrate the operation of the proposed method.

Keywords: shoe last, foot shape, deformation, custom footwear, distance map

1. INTRODUCTION

Footwear sales have shown great growth in recent years. For example, American consumer's spending on athletic footwear rose 3.6% in 2000 to $15.07 billion after two years of declining spending. In 2000, Americans purchased 405.4 million pairs of shoes at an average price of $37.17/pair (Sporting Goods Manufacturers Association, 2003). With the increasing demand, to achieve commercial success, the footwear manufacturing industry must be able to offer footwear that can fulfill consumers' requirements better than its competitors.

The fashion or style of the shoes is generally the first element attracts consumers. The exponentially increasing variation of footwear available in the market today is partially due to the various perceptions of fashion and style. Next to fashion, product fitness is also very important. It is the major criterion for the product performance evaluation. Recent studies show that unfit shoes are the principal cause of forefoot disorder. Traditionally, the footwear is cataloged by foot length and foot width for the consumers to select. However, to select a pair of shoes to fit a person's feet, the fitting ought to be more than just length and width, as different people have different foot shape and different requirements even though they may have same foot length and width [1][2]. The fit on heel width, heel to ball length, frond foot width, toe space, and so on also need to be taken into consideration [3][4].

The designing of shoe last, which represents the approximate shape of the human foot, is very important in the whole shoemaking process. "A good last for shoe production has the same importance as a good foundation for a stability of a house" [5]. It is responsible for the product fitness as well as the footwear style. The design of footwear begins with the selection or the design of the shoe last. To make well fitted footwear for a specific consumer, firstly, the well-designed customized shoe last is required.

Because of the complexity and the constraints imposed by the footwear manufacturing process, most importantly, the last manufacturing process, the custom footwear is expensive to produce. In traditional shoemaking industry, to make an accurate custom shoe last, the shoemaker must manually measure the specific consumer's foot, and sometimes, more than thirty measurements are required. The last is also manually manufactured by experienced last maker. The process of foot measuring and last manufacturing is always complicated and time-consuming.

Nowadays, with the emergence of foot scanner, automating the process of producing custom tailored footwear is reasonable if the custom last can be automatically produced based on consumer's foot shape. There are already some approaches in literature [6][7][8][9][10]. A typical idea is to select from existing shoe lasts database or deform an existing shoe last model into one that fits the scanned foot data.

For example, Luximon [6] suggested a color coded mismatch between shoe last and human foot to quantify footwear fit and predict the fit-related comfort. One application of the proposed method is to choose the 'best-fitting' last from a group of available lasts. However, it didn't give clear definition of the fit based on the color-coded mismatch.

Li [7] suggest storing rear parts and front parts of shoe last separately, and using a proposed operator to generate a smooth surface between two given disjointed surface of the rear and front part of the shoe last to generate a new last. So it can fulfill different design requirements. This method can benefit companies which already maintain a library of last rear part, so only the front part, which is also the part contain the fashion factor, need to be designed. However, this method is not very accurate for custom tailored footwear designing as the consumer's foot may vary from time to time. Moreover, it is very computational expensive.

Mochimaru [8] proposed to use Free Form Deformation to deform the shapes of the foot by moving control lattice points set around the object. A last of width EEEE is designed from an existing last of width E by applying the control lattice. However, the deformation didn't consider the reservation of original shoe last form, which contains the fashion or style factor; what's more, the method is not applicable to custom last design.

In this paper, a method is proposed to deform a consumer-preferred shoe last form to fit the specific consumer's foot shape, and preserve the original style of the selected shoe last during the deformation to an utmost extent, as the original last style contains fashion factor preferred by the consumer.

The remainder of this paper is organized as follows. The proposed deformation method is described in section 2, which includes the foot and last alignment, the setup of amendment map, the computation of distance map, and the last deformation; preliminary experimental result is shown in section3; section 4 gives the conclusions and some discussions.

2. THE METHOD

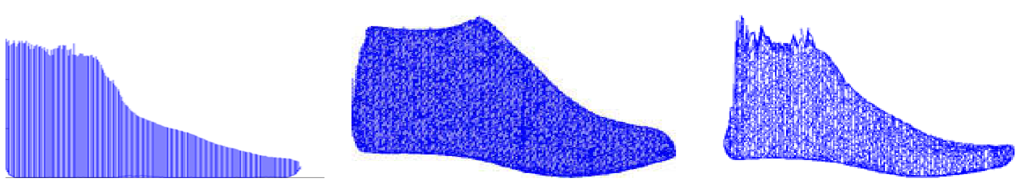
2.1 The Scanned Data and Data Alignment

The input foot and last data is collected by "InFoot" system, which is 3D foot scanner consisting of eight 1/4' progressive CCD cameras and four 670 nm Semiconductor Laser projectors.

Fig. 1. The InFoot 3D foot scanner

To make a custom-tailored shoe last, firstly, the consumer's foot shape information is collected using the foot scanner. Based on the consumer's preference, secondly, some existing shoe last form is selected as the base form. Custom last is to be obtained by deforming the shoe last base form to fit the consumer's foot information. As the last form already covers some required fashion factors to make custom footwear, when deforming the last shape to fit the consumer's foot shape to achieve the product fitness, it is important that the fashion element should be preserved.

The scanned foot and last data are shown in Fig. 2(a) and Fig. 2(b) respectively, with the sample spacing of 1mm. Basically, every shoe last has a toe spring and heel height as shown in Fig. 2(b). Before the deformation, the foot shape is 'adjusted' to account for the toe-spring and hell height of the last. The result of adjustment is shown in Fig. 2(c).



(a) (b) (c)

Fig. 2. (a) the scanned foot data; (b) the scanned last data; (c) the adjusted foot data.

The original scanned data of the foot contains 64168 sample points, while the last data contains 56122 sample points, which is more than enough to represent the object shape in our experiments. To save the computational load, we re-sampled these two data sets and use 7234 points to represent the foot shape, and 5689 points to represent the last.
The 3D foot and last are aligned here in the same way as in [1], by aligning the hell centerlines of the foot and last. The alignment result is shown in Fig. 3.

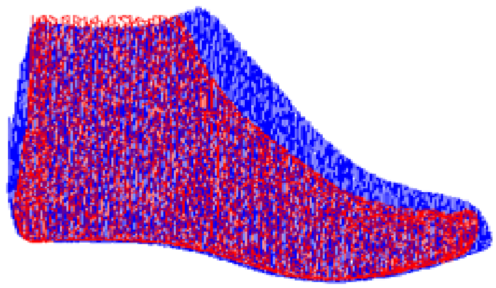


Fig. 3. Foot and last data aligned along heel center line. The foot form is shown in red, and the base last form is shown in blue.

2.2 Computation of the Distance Map

To deform the selected shoe last to fit the foot data, it is important to know how and where to perform deformation. To guide the deformation, dimensional difference between the aligned foot and last is calculated as the indication of how well the last 'fits' the foot.
The dimensional difference is calculated as following. Firstly, the surface sample points of the last are triangularly meshed. The direction of each last sample point is calculated as the average norm of the surfaces surrounding that point. Secondly, the nearest foot point is searched for along the calculated direction (positive difference) or in the opposite direction (negative difference) of this sample point. The distance between this last sample point and its nearest 'partner' on the foot is then calculated as the difference. By calculating the distance on all the sample points of the last, a 'distance map' is obtained to indicate the dimensional difference between the foot and the last.
It is important to differentiate the positive and negative differences between the foot and last data, as they have very different implications. The positive difference indicates where the last surface is outside the boundary of the foot surface, which may result in slippy footwear. The negative difference is present otherwise and indicates the places where are narrow and tide.

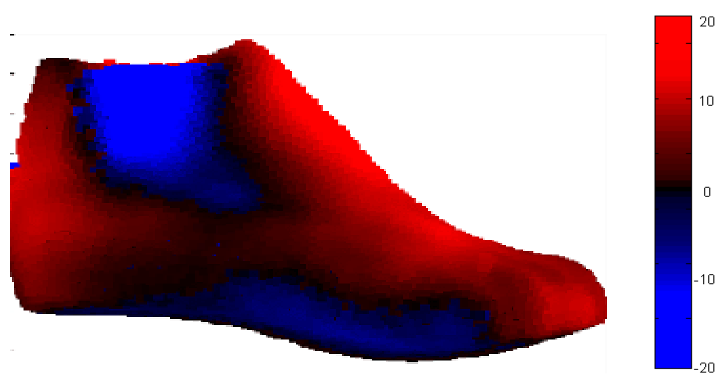


Fig. 4. The distance map calculated on the last surface, the unit of color bar is *mm*.

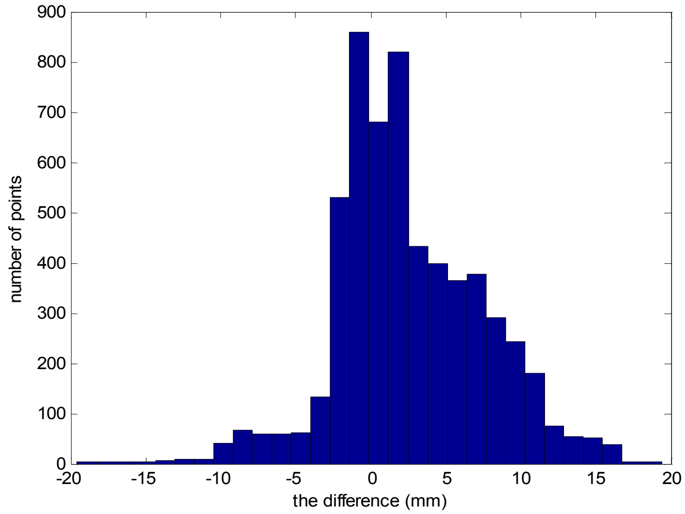


Fig. 5. The histogram of the calculated distance

The computed distance map is color coded and shown in Fig. 4. The region in red is where the positive difference occurs, while blue indicates negative difference. we can see that the last is ‘loose’ in the instep and heel seat part, where ‘tide’ around the metatarsale tibiale, netatarsale fiburale (the inboard and outboard of front part of the foot), and ankle part. As the selected last is in a low top design, the difference around the ankle part is not required to change much. The histogram of the differences is shown in Fig. 5. The largest positive and negative differences are around 2cm. Both the positive and negative differences are to be reduced.

2.3 The Amendment Map and the Deformation

It is known that large positive difference between the last and foot will result in slippy footwear, as there is too much ‘space’; and large negative difference may lead to uncomfortable and tide footwear, which sometimes even cause foot diseases. However, there are also some required dimensional differences in the last manufacturing. For example, to save space for the foot movement, proper positive differences are required in specific regions such as instep and toe region. Small negative difference around the metatarsale tibiale and netatarsale fiburale is acceptable, so that the footwear won’t be loose. As a result, to make the shoe last fit to the specific foot, instead of simply deforming the base last as close as possible to the foot form, on some specific regions of the last, specific differences are required. From section 2.2, on the i^{th} sample points from the last, a distance D_i from this point to the foot surface is calculated, as shown in Fig. 6. To fit the last to the foot shape, the sample point should be located close to the foot surface except for some specific regions that are required to keep appropriate distance from the foot surface like toe region and instep.

With this consideration, an amendment distance map, referred as *D’*, is set up offline by the experience of experienced shoe makers according to the location of this point on the last surface to cater for the required dimensional differences.

On the other hand, to keep the original style of the selected shoe last, as there is no feature extracted to represent the last ‘style’, the simplest way is to preserve the shape of original last to the utmost extent. Simply rescaling the original last form doesn’t solve the problem, as simply scaling the last to fit the foot in one region may result in increasing dissimilarities in other regions. As it is well-known that the front part, especially the ‘toe cap’, of shoe last carries a lot of the fashion factor, preserving the front part shape of the last during the deformation can help a lot in preserving the overall last style. This requirement is also incorporated when setting up the amendment map.

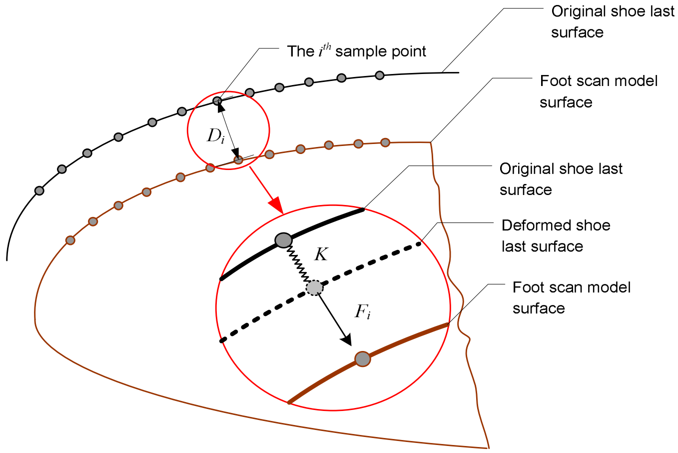


Fig. 6. The difference D_i between last and foot surface and the defined force F_i

Assume each sample point of the last is moved by a certain displacement in the process of deformation, and the displacement is designed to have two components.

Firstly, the last is slightly scaled by a coefficient t_1, which can be seen as each sample point moving along the calculated direction for a certain displacement. This movement can reduce/increase the difference between the last and foot form in a whole without effect the last shape.

Secondly, suppose there is a deform force F_i on the i^{th} point drawing the point towards a new position to fit the foot shape. Based on the calculated distance map and the amendment map obtained offline, the deform force is defined in ratio of the 'amended distance map', that is $F_i = \alpha\ (D_i - D')$, where □ is a constant to convert the distance unit into force unit. For example, if the i^{th} sample point is located at the tip of the last, the calculated distance D_i from the distance map indicates how far it is from the foot tip; from the last manufacturer's experience, in order not to hinder the toe movement, around 10mm should be added to the toe end when making a last. So, for sample points located at the toe region, positive difference *D'* should be remained after deformation, where *D'* is the information set up based on last manufacturing experience and vary with the different place of the last surface.

The direction of the deform force is along the calculated direction of each sample point. The displacement under *F* is applied to make up for the dissimilarity between the foot and the last to approach 'fitness'. To prevent the point from moving infinitely, a counterforce simulated as a 'spring' is applied, as shown in Fig. 6. We get:

$$K \cdot \Delta x_i = F_i \tag{1}$$

where Δx_i is the displacement produced on the i^{th} sample point and K is defined in the form of

$$K = k \cdot \Delta x_i \tag{2}$$

where k is a constant. We can see that K increases with the increasing of Δx_i, which means the 'spring' becomes stiffer as the point moving away from the original position, and can restrain the dissimilarity between the original last shape and the last shape after deformation.

From equation (1) and (2), we can get: $\Delta x_i == t_2 \cdot \sqrt{|D_i - D'|} \cdot \mathrm{sgn}(D_i - D')$, where $t_2 = \sqrt{\frac{\alpha}{k}}$.

So, to deform and fit the reference last form into the consumer's foot with the proper movement on each sample points of the scanned shoe last, two variants t_1 and t_1 are to be calculated. The variants can be calculated by minimizing the following equation:

$$E = \beta \cdot \sum_i (P_i^{Foot} - P_i^{last}) + \sum_i (\Delta x_i)^2 \tag{3}$$

where the first term calculates the Euclidean difference between the foot and the new last after deformation, and the second term presents how much the new last is changed in shape compared to the original last. The coefficient□is a constant controlling the trade off between preserving of the last shape and the fitting into the target form, which can be changed according to different requirement. In our experiment, β is set to 1. Optimizing the two unknown parameters t_1 and t_1 is an ill-posed problem, because the number of sample points is much larger than the variants. In the result, by minimizing equation (3) using Sum of Squared Differences method(SSD)[11], the base last can be deformed to fit the consumer's foot better with the minimal change to the original style of the base last form.

3. EXPERIMENTAL RESULT

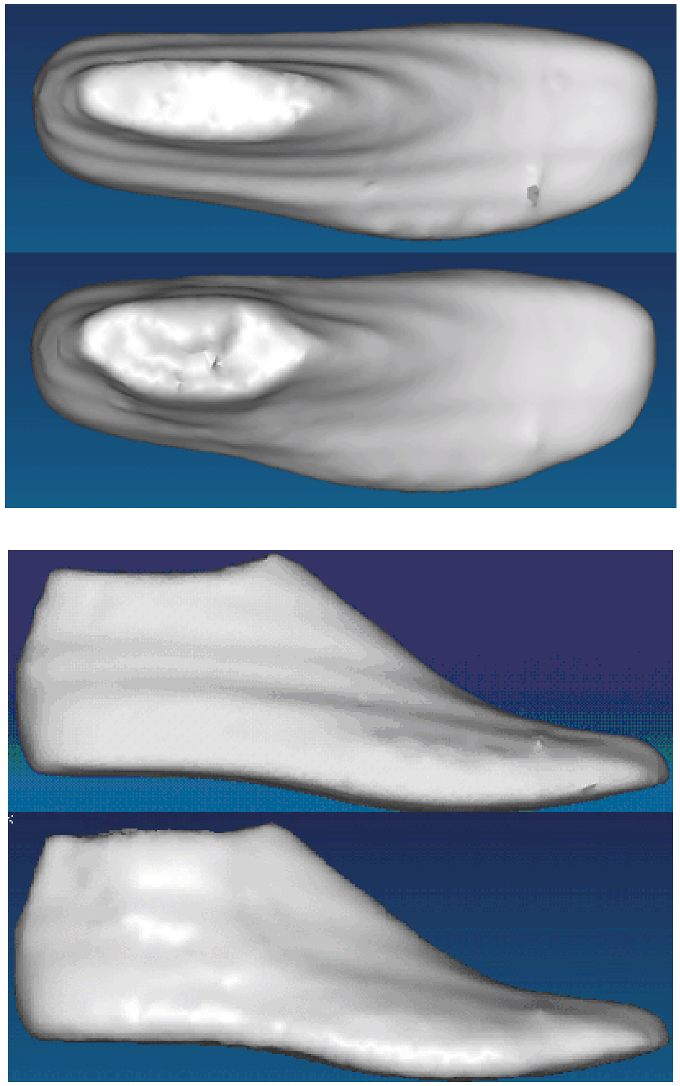
The deformation method is programmed by MATLAB, and the unit for the implementation is *mm*.

To verify our proposed method, we simply define *D'* as such that around the ankle part, $D_i' \approx (1-\frac{\mathrm{sign}(D_i)}{\sqrt{|D_i|}})D_i$, so the deform force around ankle is much smaller than other region as this part is not required to change a lot; around the toe region, *D'* is set as a function of D_i to keep spacing for toe movement as well as to keep the 'toe cap' deform smoothly to preserve the original style. For example, we can set $D_i' \approx D_i - (d - 8mm)\cdot G$, where *d* is the difference calculated on the tip point of the last. *G* is a function defined on the distance from the i^{th} sample point to on the tip point on the last surface.

By using the foot and last data shown in Fig.2, the calculated t_1 and t_2 are 0.9881 and 1.2505 respectively. The deformation result is smoothed to remove noise, which may be aroused by the falsely calculation of surface norm, and shown in Fig. 7 and Fig. 8.

Fig. 7. The shape in red is the deformation result. The foot is shown in blue, and the original last form is shown in black.

In Fig. 7, the deformation result is shown in red, the foot shape is shown in blue, and the original last form is shown in black. We can see that the last after deformation can fit the foot shape much better than the original last. From Fig. 8A, we can see that the last style is well preserved. Slight change in the ankle part is observed, which is acceptable but still avoidable if *D'* is better evaluated. More detailed experience information (stored in *D'*) can improve the performance of the proposed method.



A

B

Fig. 8. The difference between the deformed last and the original last. In each figure, the upper one is the original last form and the lower one is last form after deformation

4. CONCLUSIONS AND DISCUSSIONS

The idea of deforming existing last model to fit consumer's foot shape with minimally affecting the original last style is proposed in this paper. The goal is to deform a custom preferred shoe last form based on the consumer's foot shape to obtain a custom tailored shoe last, which maximally preserving the fashion factor or the style of the original last. To perform the deformation, a distance map is obtained by calculating the difference between the foot and original last form; an amendment map setup offline based on last design regulations is also utilized to guide the deformation. The proper movement on the sample points of the original last is calculated by minimizing the SSD of equation (3), by which we approaches a better fitted last and preserves the original last style at the same time. From the experimental result, although no detailed experience information is imported, we can see that the last form after deformation fits the specific foot shape much better than the original one, and the last style is also well preserved.

However, though our preliminary experimental result is quite acceptable, detailed experience information is very important especially when applying the proposed method to deform shoe lasts containing a lot of style factors, such as high-heels with crakow. Another consideration is that, if we can represent the shoe last 'style' by some features instead of using the whole last shape, preserving the last style during deformation will be much easier and more reliable.

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