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A SYSTEM FOR FOOTWEAR FITTING ANALYSIS

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1. Introduction

A shoe making industry which can offer shoes that fit consumer needs has a decided advantage over its competitors. Next to fashion, shoe fitness is an important selection criterion. To acquire consumer foot information, the shoemaker should have foot size information system. Such a system should collect consumer foot data for further analysis such as shoe last design and population distribution as well as for communication with customers.

Normally, the shoemaker collects basic statistics through sales or systematic foot measurement [Anil et al. 1997]. A statistical analysis relies on only few parameters, e.g. foot length, width, and breadth, as the complexity increases exponentially with each variable.

The proposed fitting measurement system is intended to be installed in shops where, firstly, customers' feet are scanned and, secondly, shoe database suggest best fit shoe models. We are going to describe the matching software part of the system that consists of a computer and a laser scanner.

A typical approach for customer tailored shoes consists of deforming an existing shoe last design into one that fits the scanned foot. This type of tailored shoe production is only reasonable if used in clinical orthopaedic cases, e.g. diabetes, gout. There are specialised tools for such requirements (Shoemaster, Vorum) that provide custom shoe last design with local modification of the scanned shoe last mesh. The scanning procedure requires a lengthy preparation of a foot of each customer who must wear white socks on which the operator marks four or more black landmarks for bone recognition and foot orientation. For the scanning process to complete successfully, the customer must stand still for several seconds. An adjustment procedure is repeated for the other foot. A surface laser scanner for a large volume scanning with minimal operator intervention has been developed. The scanner fulfils the requirements in speed, ambient light insensibility, accuracy and production costs.

Four lasers project line matrices that are recognised with mating CCD cameras. The image processing part of each camera produces a fixed number of profiles that can be described as polylines in space. Moiré profilometry is used for profile generation. The space density of points in the profile is normally much greater than the inter-profile distance. For each camera one can create a surface patch which, when combined together, represents a complete surface of the foot. A calibration for the region of interest is performed for each scanner camera.

The creation of a combined surface includes a triangulation with curvature sampling and patch overlapping removal. The scanner has no moving parts and is thus reliable. The capture speed is less than 300ms. No landmark stickers are needed for scanning. The recognition of foot bones relies solely on software. This type of foot analysis requires a completely new approach with feet database for the comparison of scanned feet with the foot database. Database feet have marked measurement positions for all parameters of interest which are then combined with a weighting function to a single measure of comfort when searching for shoes of the highest comfort.

2. Fitting

Shoe lasts can be scanned in the same way as feet and stored in the shoe last database. When the foot is scanned, the reconstructed surface needs to be transformed into a position compatible with the shoe last. For simple shoe last geometry Mochimaru et al. (2000) suggests a space deformation technique that can deform measured points bounded by a control lattice. In order to create a shoe-grading system the manufacturer has to collect several measurements for each individual and design shoe lasts that will conform to the grading standard [Cheng et al. 1999]. The produced shoe model should cover the target population in terms of size, fashion and price.

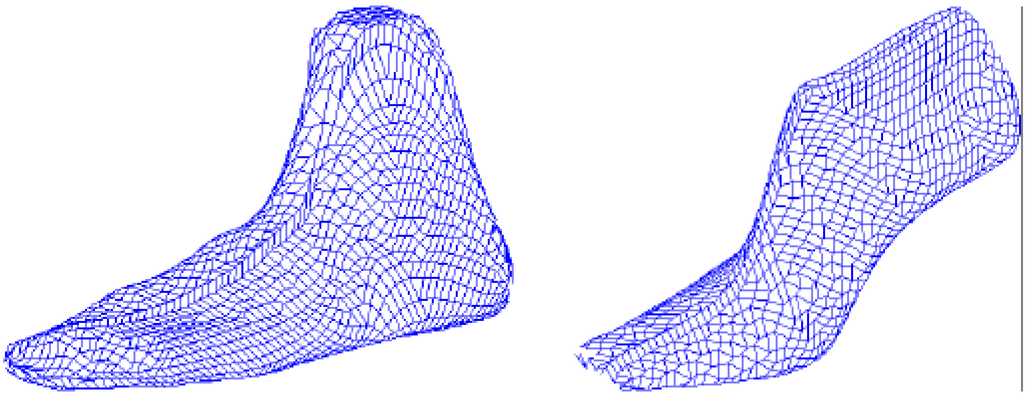

Figure 1. A wireframe model of the foot (left) and shoe last (right)

Basically, every shoe last has a toe spring and a heel height. Besides these two parameters the shoe last includes several manufacturing requirements such as insole, lace and dorsal arch space, ease of manufacture, and fashion. Thus, the shoe last shape is not an exact copy of the foot. Foot deformation into a high heel position as shown in Fig. 1 is not so simple. Techniques such as FFD [Mochimaru et al. 2000] or warping to the silhouette of the shoe last sole will not produce satisfactory results for such cases. Using an analytical model of foot bones that will lead to surface deformation could produce useful results. Current efforts to model a complex structure of 28 bones are concentrated on the measurement of a simplified kinematics complex [Carson et.al. 2001, Liu et.al. 1997]. It is suggested by Kouchi/Mochimaru. (1999) that the bone structure is not consistent with the surface model due to different thickness of the sole soft tissue.

We propose that the scanned foot in the flat position should be matched with a similar foot from the database to obtain landmark similarities for the fitness analysis. As the scanned foot has no landmarks for accurate positioning of the landmarks from which the fitting parameters are derived one has to rely on the registration of surfaces.

3. Surface registration

The two surfaces are not guaranteed to have the same position in the world coordinates, which is required for an accurate fitting comparison. As the surface description with triangles is sparse, we have developed a method for iterative surface matching based on Iterative Closest Point method [Besl et al 1992]. Our algorithm can register surfaces with sparse description and different sampling.

3.1 Computing the rigid motion

The purpose of the method is to find rotation and translation, which minimises positional error from points on the one surface to the nearest points on the matching surface. Minimising the following mean-squares objective function

$$F(\mathbf{R},\mathbf{t}) = \frac{1}{N}\sum_{i=1}^{N}\left\|\mathbf{R}x_i + \mathbf{t} - y_i\right\|^2 \quad , \tag{1}$$

will compute rigid motion (**R, t**) of N point pairs on the first surface $\{x_i\}$ to the set of $\{y_i\}$ nearest points on the reference surface.

Among several iterative optimisation methods we have implemented a dual quaternion method which is capable of solving minimisation without iterations. In the following, the dual number quaternion method [Walker et al. 1991] is summarised.

A quaternion **q** can be considered as being either a 4-D vector $[q_1, q_2, q_3, q_4]^T$ or a pair (**r**, q_4) where $\mathbf{r}=[q_1, q_2, q_3]^T$ is a rotation vector and q_4 is a scalar. A dual numbers such as dual quaternion have dual part **s** where a special multiplication rule applies $\varepsilon^2 = 0$. A dual quaternion **d** thus consists of the two quaternions **q** and **s**, i.e.,

$$\mathbf{d} = \mathbf{q} + e\mathbf{s} \,. \tag{2}$$

A rigid 3-D motion can be represented by dual quaternion **d** satisfying the following two constraints

$$\mathbf{q}^T\mathbf{q} = 1 \text{ and } \mathbf{q}^T\mathbf{s} = 0 \tag{3}$$

A 3-D vector **x** can also be identified with quaternion with zero scalar part (**x**, 0). It can be easily shown that rigid motion can be described as

$$\mathbf{Rx} + \mathbf{t} = \mathbf{W}(\mathbf{q})^T\,\mathbf{Q}(\mathbf{q})\mathbf{x} + \mathbf{W}(\mathbf{q})^T\,\mathbf{s} \,, \tag{4}$$

where matrix functions of quaternions are defined as

$$\mathbf{Q}(\mathbf{q}) = \begin{bmatrix} q_4\mathbf{I} + \mathbf{K}(\mathbf{r}) & \mathbf{r} \\ -\mathbf{r}^T & q_4 \end{bmatrix}, \; \mathbf{W}(\mathbf{q}) = \begin{bmatrix} q_4\mathbf{I} - \mathbf{K}(\mathbf{r}) & \mathbf{r} \\ -\mathbf{r}^T & q_4 \end{bmatrix}, \; \mathbf{K}(\mathbf{r}) = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix}. \tag{5}$$

Adjoining the constraints (Eq. 3), the optimal dual quaternion is obtained by solving the following Jacobi Eigensystem equation

$$\mathbf{Aq} = l_1\mathbf{q} \,, \tag{6}$$

with quaternion **q** as eigenvector of matrix **A** and l_1 as the corresponding largest eigenvalue. Matrix **A** is defined as

$$\mathbf{A} = \frac{1}{2}\left[\frac{1}{2N}\mathbf{C}_2^T\mathbf{C}_2 - \mathbf{C}_1 - \mathbf{C}_1^T\right], \tag{7}$$

where

$$\mathbf{C}_1 = -2\sum_{i=1}^{N}\mathbf{Q}(y_i)^T\,\mathbf{W}(x_i) = -2\sum_{i=1}^{N}\begin{bmatrix} \mathbf{K}(y)\mathbf{K}(x) + yx^T & -\mathbf{K}(y)x \\ -y^T\mathbf{K}(x) & y^T x \end{bmatrix}, \tag{8}$$

$$\mathbf{C}_2 = -2\sum_{i=1}^{N}\left[\mathbf{W}(x_i) - \mathbf{Q}(y_i)\right] = 2\sum_{i=1}^{N}\begin{bmatrix} -\mathbf{K}(y) - \mathbf{K}(x) & x - y \\ -(x-y)^T & 0 \end{bmatrix}. \tag{9}$$

Explicit form of the $\mathbf{C}_2$ can be written with Cartesian indexes as

$$\mathbf{C}_2 = 2\sum_{i=1}^{N}\begin{bmatrix} 0 & y_z - x_z & x_y - y_x & x_x - y_x \\ x_z - y_z & 0 & y_x - x_x & x_y - y_y \\ y_y - x_y & x_x - y_x & 0 & x_z - y_z \\ -x_x + y_x & y_y - x_y & y_z - x_z & 0 \end{bmatrix}, \qquad (10)$$

which is also used for the calculation of the translation part **t** in (Eq. 4), where quaternion **s** is given by

$$\mathbf{s} = -\frac{1}{2N}\mathbf{C}_2\mathbf{q}. \qquad (11)$$

Scalar part q_4 of the translation quaternion **t** is always zero.

3.2 The iterative algorithm

Although computing of the rigid motion is one pass algorithm, finding corresponding points on surfaces is not known in advance an thus the motion must be repeated form a very rough estimation $(\mathbf{R_0},\mathbf{t_0})$. The algorithm consist of two iterated steps, at each iteration *i* computing a new estimation $(\mathbf{R}_i,\mathbf{t}_i)$ of the rigid motion:

1. Find corresponding a set of pairs of points. For each point x_i find the nearest point on the reference surface y_i.
2. Calculate rigid motion as described in section 3.1 and apply it to all points of the surface **x**.

The termination criterion can be set when the variation of the distance between the two surfaces at two successive iterations is below a fixed threshold or when a maximum number of iterations is reached. In this iteration process, surface **y** is fixed in reference space and surface **x** is aligned to it. Finding nearest neighbour points on **y** for each x_i can consume most of the iterative time. Recognising that search space of the surface **y** does not change one can subdivide space of this surface into search efficient "kD-tree". Additionally, Arya, et al. (1994) shows that, if the user is willing to tolerate a small amount of error in the search, it is possible to achieve significant improvements in running time.
Initial displacement can be significant as shown in Fig. 2. (Dotted is initial position) and due to the convex nature of the surface there are no local minimums. Surface pairs are shown in Fig. 2 right.

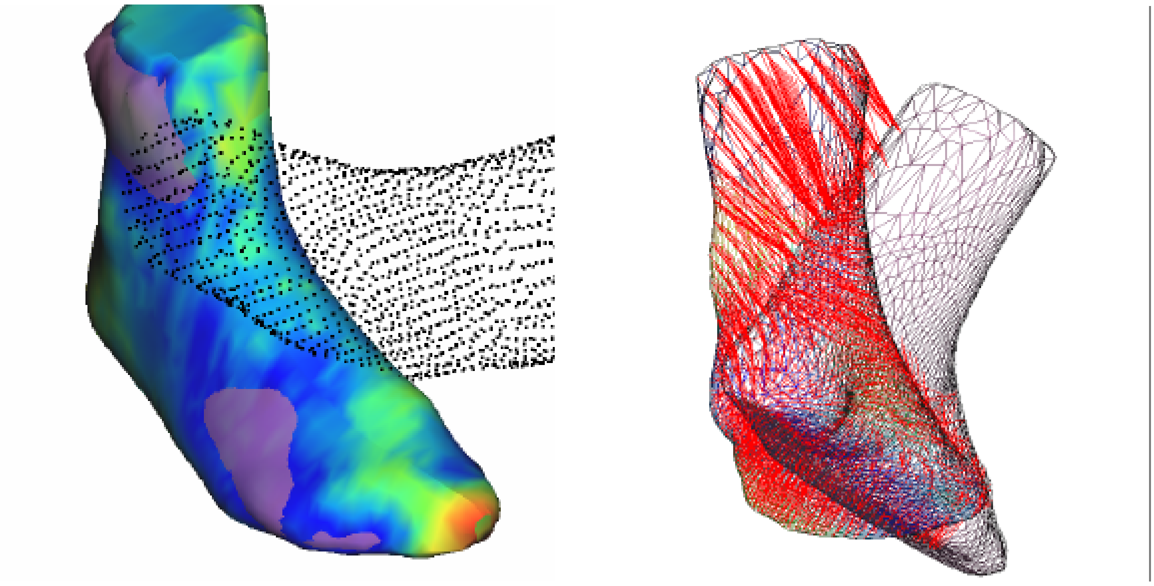

Figure 2. Registration and fitness function mapped on the aligned surface (left). Force vectors (right)

4. Fitness function

With registered surfaces one can compare the two volumes for fitting. Normally, the shoe length and joint girth are used for the fitting measurement, as other measures can be adjusted with laces. The front part of the shoe is designed to meet fashion requirements and the rear fulfils biomechanical properties. For this reason simple geometrical distance comparison is not appropriate. One can use cross-sections at predefined positions and measure dissimilarities of circumference, width, height, joint girth, waist girth, instep girth and other dimensions. We propose to use a weighted cost function which can determine foot fitness as a single value and also as a weighted distance function on the surface. This also means that there must be a foot size information system with reference feet that have marked positions with cross section positions. The measure of comfort is difficult to access, because besides geometry one must also evaluate shoe materials uses (sole and upper). Generally, we can write down the weighted comfort measure of the registered surface ***x*** as

$$F(x) = \sum w_i p_i(x) . \tag{12}$$

Each parameter $p_i(x)$ can have its own evaluation function and is weighted with w_i. User functions in the implemented software allow automated girth, projection and length measurements. Most of the comfort could not be measured or formulated with scientific knowledge in the current technology. For complex decisions one can also apply a decision process such as AHP [Žavbi/Duhovnik 1996].

5. Case study

For the purpose of approach evaluation and testing of the registration we performed fitness correlation with a simple fitness function of the volume difference between registered surfaces. The foot length was normalised to 270 mm. The registration height was limited to lower 80 mm in order to rule out differences in stance and ankle surface. The basic question was: "Is there a shape of foot that matches (fits) equally well to all other feet?" What is the distribution of foot shapes?

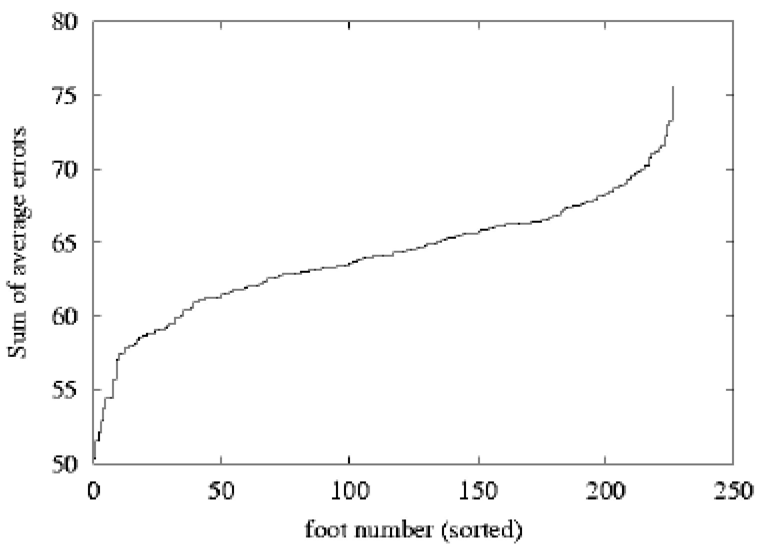

Figure 3. Fitness correlation between individuals

Figure 3 shows the result of 52670 correlation evaluations sorted by registration error i.e. volume difference as mean inter-surface distance. The graph shows that there are some foot shapes that fit equally well to all other shapes (low error numbers) and there are some very dissimilar foot shapes. Designing shoes for this "master" shape should be a safe decision for the manufacturer. Including only common shapes in the database for the matching process also minimises search space as this correlation can be regarded as the precompiled fitting database.

6. Conclusions

In this paper, we proposed a complete system for footwear fitting measurements which is tailored for in-shop measurement. A successful introduction of such system can open several so far unfamiliar areas of e-shoe business such as design of well fitting products, lot sizing, internet shoe sales and special per customer offers.

The fitting of the shoes is measured with a weighting function of several user-defined parameters. No explicit directions are given for a synthesis of such a function, but an experienced manufacturer should be able to come up with some guidelines.

Over 1000 feet (66%F/34%M) and several shoe lasts were scanned for the purpose of a statistical and fitting analysis. Some results in building a foot size information system were presented in the case study. More systematic information on the relation between the foot and shoe last (or shoe in general) is needed to make a robust fitness measure.

The application development concentrated on the visualisation. A universal approach of the OCX ActiveX communication isolates engine from user interface (UI). Several UI were built on top of the engine. But for approaches as the one in the case study, triangulation of the surface for visualisation was unnecessary overload for batch processing.

Further work should concentrate on the fitness database design. There are no guidelines on how to transform shoe last measurements to a matching foot. A statistical analysis will surely open new questions which will require specialised tools as those presented.

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