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Computer Aided Design and Development of Customized Shoe Last

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ABSTRACT

The paper presents a work that shows an application of digital modeling of human body where CAD has been applied to design and develop a customized shoe last. The customization process has been divided into seven steps which have been mathematically modeled and implemented automatically through a program. The process starts with the generation of point cloud definition of the foot and existing lasts with an Optical Scanner. The point cloud data are registered and processed, and the last closest to the foot in shape and size is selected. B-spline curves and surface patches are fitted on to the point cloud of the last to generate a water-tight geometry of the last. The surface patches are then diagnosed and edited to conform to the geometry of the foot in the desired manner and a modified version of the last is prepared. This version is converted to STL file and rapid prototyping (RP) technology is used to fabricate a sample of the customized shoe last. The file can also be used to generate codes for CNC machining of the lasts in case of mass customization.

Keywords: shoe last, customization, point cloud data, surface fitting.
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1 INTRODUCTION

1.1 Background

Footwear is the need of every human being. Recent studies show that unfit shoes are the principal cause of forefoot disorder [11]. Shoe design has three aspects: ergonomic, functional and aesthetic, and all three are important though the degree of importance may vary from person to person. In general, footwear is categorized by its length and the width. However, keeping the length and the width the same, different consumers may have different foot shapes and have different requirements. In order to find a pair of shoes that perfectly fit the customer's choice, custom-tailored footwear is necessary. Recent development in technologies such as CAD/CAM and RP has made it possible to design and fabricate shoes as per the need of each customer. Such footwear will be especially useful for patients with podiatric disorder. The demand for such footwear is on the rise, especially in European and American markets. Indian footwear industry has tremendous potential in the domestic market as well as for export. One needs to develop methodologies and user-friendly tools to create job opportunities.

1.2 Various Aspects of Footwear Design

To manufacture a shoe, one has to take into account three major constituents: (i) shoe upper (ii) shoe last and (iii) sole. The fit of a shoe depends greatly on the shoe last [11]. Several styles of shoes can be made with one pair of shoe lasts. The design of good lasts is a masterpiece of engineering and a work of art on which depends the fitness, quality and appearance of the finished shoe. A shoe last can be categorized by the material, style, production method and usage occasion. In general, several important measures are available for a shoe last. Change of last sizes determines whether these measures will be increased or decreased. These major measurements include [4]:

(1) foot length,
(2) joint, waist, and instep girth,
(3) heel pitch,
(4) toe spring, and
(5) bottom width.

1.3 Need for Customized Shoe Last

An understanding of the structure and biomechanical characteristics of the foot [4] shows that it has twenty six bones which can be categorized into three groups: the phalanges (forming the front part), the metatarsal bones (forming the middle part) and the malleolus bones or tarsal bones (forming the back part of the foot). The design of a shoe last mainly focuses on the forepart while the back part of a shoe last almost remains the same. Ill-fitting footwears cause foot deformities and lesions. Some people have abnormal feet (Fig. 1), i.e. the feet do not conform to any size system. Irregular shapes, projecting fingers or deformities caused due to diseases or accidents are examples of such cases. In such cases, customized shoes are of utmost importance.

1.4 Literature Review

Leng and Du [11-12] have presented a CAD framework for designing customized lasts consisting of a global deformation approach that can automatically form a customized shoe last based on scanned foot data and an existing shoe last data, and an interactive local deformation method. Cheng and Perng [4] have analyzed the foot length and joint girth by using a bi-variate normal distribution to obtain a more efficient foot size grading system and established a foot size information system (FSIS) providing shoe last related information; such as the percentage of population that a last can fit in. Braha and Maimon [2] have developed an approach for creating a virtual shoe last by constraining a series of 22 3-D Bezier curves to satisfy a set of measurements given by designer. Hwang et al. [5] have derived the geometric models of template shoe-lasts by grouping various existing shoe-lasts into manageable number of groups and quantified the similarity between shoe-lasts for grouping similar shoe-lasts into respective groups. Lee et al. [10] fabricated several strangely shaped foot models and reconstructed CAD models using stereovision technique for a low-cost foot scanner. Chen et al. [3] have presented an integrated CAD/CAM system development approach for shoe last. The shoe last model has been presented by a regular surface point data set. Manipulating the data set has allowed the design process to be realized. The data set is used to construct surface model of shoe last.

Fig. 1: Cases of abnormal feet [15].

Alcántara et al. [1] have developed a graphical tool called semantic profile to interpret and analyze the results of product semantics on either a single product (individual semantic profile) or for comparing two products (compared semantic profile) and applied it to shoe design. Jimeno et al. [6-7] have developed a tool-path generation algorithm that takes advantage of traditional copier systems that do not fulfill the CNC standards. A virtually digitized model of the last surface allows the tool path to be computed and is followed by a series of optimizations. The proposed algorithm was successfully implemented in a commercial CAD/CAM system specialized for shoe-last making. Paris and Handley [13] have addressed the process of design and development of shoes using CAD/CAM and knowledge based systems. The process of collecting knowledge, formulating this into rules and using to select best fit shoes has been outlined. Tools to convert best fit shoes into custom fit shoes are also described. Kim et al. [8] have proposed a grouping method, which helps in fabricating custom-tailored products quickly. A prototype system based on the proposed methodology has been implemented and used to group the shoe-lasts for custom-tailored shoes. Lai and Wang [9] have developed an effective image-processing method to automatically extract the boundary of a shoe pattern. In the study, they first used a histogram thresholding technique to segment out a shoe pattern from the scanned input image. Wang [14] has developed an algorithm to identify the most suitable last for a foot among the available ones using fuzzy theory and an analytical hierarchy process.

In the present work, a complete and simplified methodology which has not been reported in the literature yet, has been developed to customize the shoe last using CAD and an optical scanner. The implementation of the methodology has been accomplished in a surface modeling environment, Surfacer V10.0. For this, the foot and the nearest matching existing shoe last have been scanned using ATOS 3D Digitizer. The scanned data gave the point cloud. Then the two point clouds have been compared and the difference between the clouds has been marked. There after, a surface fitting has been done on the point cloud data of the last with the help of Surfacer. Then the surface has been modified using the control points on the surface to match the foot. Since the rear part of the last matches the foot when the approximately fitting last is selected, the modification has been done on the front part only. Once the modified last is ready, it has been rapid prototyped on a FDM machine. This model is ready to make the shoe which fits the foot better.

2 DESIGNING A CUSTOMIZED SHOE LAST

When designing products with free form shapes such as shoe lasts, shape information can be acquired as a set of data points called point cloud and then the surface patches can be designed. The design of the customized shoe last involves the following steps:

(i) Scanning and generation of point cloud data for foot
(ii) Scanning and generation of point cloud data for existing shoe lasts
(iii) Comparing the point cloud data of the foot and the last
(iv) Selection of last closest to the foot
(v) Generating curves with tangent continuity over the last
(vi) Creating surface patches over the last
(vii) Diagnosing the surface patches and modifying them to fit the foot

2.1 Scanning and Generation of Point Cloud Data for Foot

The foot under consideration is to be scanned to generate its point cloud definition. The foot can be scanned using a laser scanner or a while light scanner. For full customization of the last, the complete foot is to be scanned. The foot has to be rotated to have a thorough scan. Coupled with this, the throbbing of the foot during scanning is likely to create loss or overlap of data. Hence the reference points have to be fixed closely, and the resolution of the scanner has to be adjusted. As an alternative, a replica of the foot can also be created to get a good point cloud data. Subsequent treatment of the data is done by transforming the point clouds, which are obtained in any standard data format, or registering into any coordinate system. This is followed by refinement of point clouds where the clouds can be recomputed using the re-computation function and the overlapping areas of point clouds are removed. The point cloud can also be converted into a triangle mesh without overlapping areas. This is required when during post-processing one discovers that rather small features have not been defined with sufficient quality.

2.2 Scanning and Generation of Point Cloud Data for Existing Shoe Lasts

Having scanned the foot, shoe lasts of matching sizes and chosen shoe style have to be scanned. Generally the style of shoes is different for men and women. Scanning the last is far easier than the foot as it is a rigid body and does not need the detailed preparation as required for a foot.

2.3 Comparing the Point Cloud Data of the Foot and the Last

After scanning the last and the foot, the two have to be aligned. Since, the foot is asymmetric, the shoe and the last have to be aligned using an algorithm. One way to do it is to choose three points on the last and the shoe, and pass planes through the respective three points. Then the two planes can be aligned. Two planes need to be chosen on each of the last and the foot for proper alignment. One plane can be chosen parallel to the base and another along any of the girths. The planes can be formed using any standard methodology. At any point common to the two respective planes, the normal vectors are calculated and one is transformed to align with the other. In case the alignment needs to be refined, the chosen points for the plane are changed unless the alignment is acceptable to the user.

After the shoe and the last are aligned, the point data clouds are compared. In some areas, the last forms the outer area of the combined point cloud data while in others the foot forms the outer area. If the given last is used for the foot, the shoe will pinch in the areas where the foot juts out of the last and be hollow where the foot is much inside the last. This feature is particularly important for abnormal feet.

2.4 Selection of Last closest to the Foot

After aligning all the available lasts and comparing the data, the last that needs minimum rectification is selected. This can be done visually but in this work, it is done mathematically by using the exclusive-OR operation. The intersection of the two scan data is subtracted from the union of the two. The last which gives the minimum difference is to be selected. Mathematically it is expressed as:

$$\min(F \cup L - F \cap L)$$

where F refers to the foot volume and L refers to the last volume.

2.5 Generating Curves with Tangent Continuity over the Last

Data points of the last are selected and 3D B-splines curves are passed through them. To obtain the control points from the data points, the following method is used:

Let the data points on any curve be $\vec{q}_0, \vec{q}_1 ... \vec{q}_n$. To fit them with a B-spline curve of order $p \le n$, we select a set of parameters $s_0, s_1, ... s_n$ corresponding to each data point. If the unknown control points are represented by $\vec{c}_i, i = 0...n$, we have

$$\vec{c}(u) = \sum_{i=0}^{n} N_{p,p+i}(u)\vec{c}_i \tag{2.1}$$

Using the mapping of the data points and the parameters, we have,

$$\vec{q}_k = \vec{c}(s_k) = \sum_{i=0}^{n} N_{p,p+i}(s_k)\vec{c}_i, \quad k = 0...n$$

$$\text{or, } \{Q\} = \begin{bmatrix} \vec{q}_0 \\ \vec{q}_1 \\ \ldots \\ \ldots \\ \vec{q}_n \end{bmatrix} = \begin{bmatrix} N_{p,p}(s_0) & N_{p,p+1}(s_0) & N_{p,p+2}(s_0) & \ldots & N_{p,p+n}(s_0) \\ N_{p,p}(s_1) & N_{p,p+1}(s_1) & N_{p,p+2}(s_1) & \ldots & N_{p,p+n}(s_1) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ N_{p,p}(s_n) & N_{p,p+1}(s_n) & N_{p,p+2}(s_n) & \ldots & N_{p,p+n}(s_n) \end{bmatrix} \begin{bmatrix} \vec{c}_0 \\ \vec{c}_1 \\ \ldots \\ \ldots \\ \vec{c}_n \end{bmatrix} = [N]\{C\} \quad (2.2)$$

$$\text{or, } \{C\} = [N]^{-1}\{Q\} \quad (2.3)$$

Eqn. (2.3) creates B-spline interpolating curves from specified points. If somehow, the chosen curve is closed, then it has to be snipped and blended before interpolating. The number of control points and the data points chosen is going to be the same. The parameters used for interpolation can either be chosen uniformly or non-uniformly. Generally 4 to 6 control points are used to trace the curve which is kept as close to the last-surface as possible. Since the modification of the last is done mostly near the toe, the number of control points is kept higher near the toe.

2.6 Creating Surface Patches over the Last

After creating the curves, the blending of the curves can be done to create surface patches. The surface is created by interpolating the boundary curves. If a 2D curve on surface or a surface boundary is selected, the resulting surface can be forced to be position, tangent plane, or curvature continuous at that boundary. If a 3D curve is selected, the user cannot specify tangent plane or curvature continuity at that boundary. However, he/she can specify position or implied tangent continuity at that boundary. If implied tangent continuity is specified at a boundary defined by a 3D curve, the tangent direction at that boundary is obtained from the neighboring two curves. This is especially useful when creating one half of a model that must be mirrored about the center plane to get the other half. The surface created will be along the tangent direction specified by the normal of the center plane. It should be noted that the neighboring curves should be built with implied tangent continuity specified by the normal to the plane. For curves on surface or surface boundaries, implied tangent continuity is unnecessary since they can specify exact tangent plane or curvature continuity at those boundaries.

2.7 Diagnosing the Surface Patches and modifying them to fit the Foot

After fitting the surface patches, the surface cloud difference can be calculated. The areas where the foot projects out of the last are chosen to modify the last first. Using the control points, the surface is modified. The control points can be moved successively and the surface-cloud difference can be calculated. In the front part there is space between the foot and the last which has to be maintained. The last can be brought closer to the foot in the areas touching the fingers. In this process, the surface can be smoothened, the twists can be removed, the patch can be wrapped to the cloud, the surface can be re-parameterized and even the knots can be removed or inserted. By suitable modifications of the surface patches, a new shape of the last is obtained. This gives the customized shoe last.

3 IMPLEMENTATION

The scanning of a chosen foot is carried out on the ATOS white light scanner and a surface model of the foot is created with the help of Imageware's Surfacer V10.0. By putting reference points on the foot it is scanned directly (Fig. 2(a)). Scanning of foot creates loss and overlap of data due to rotation and throbbing of the foot (Fig. 2(b)). Hence, for better results, a replica of the foot is created and the scanning is done (Fig. 2(c)). With the replica, better results are obtained (Fig. 2(d)).

As the chosen foot is of size seven, hence, shoe lasts of size seven are selected. After fixing the reference points over the last and spraying the developer, the lasts are scanned. Fig. 3 shows the lasts as Gouraud shaded.

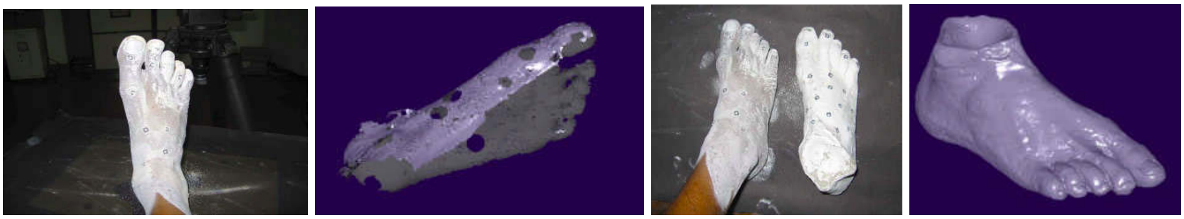

Fig. 2: (a) Foot with reference points (b) Loss of data in scan when directly scanning the foot (c) Comparison of the foot and the replica (d) Gouraud shaded point cloud data of the foot replica.

Fig. 3: Scans of Shoe Lasts of different designs of size seven.

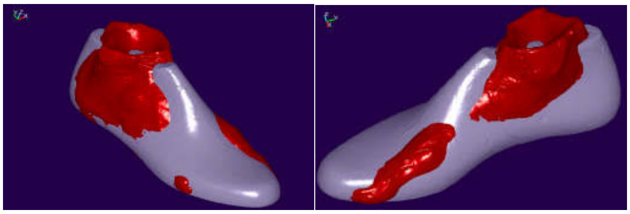

Fig. 4: (a) Right side view of the shoe last and the foot aligned together, (b) Left side view.

Then the lasts and the foot are aligned one by one. For aligning, two planes are chosen on the last and foot and aligned using the normal vector (Fig. 4). Some inbuilt functions are available in Surfacer for aligning but they work only as a preliminary step to the aligning procedure. The union and intersection of the two scans along with their difference are calculated every time. Out of all the scanned lasts of size seven, the last closest in shape to the foot post comparison is selected. The last has a cut towards the heel which makes it bendable. This joint is used to bend the last while taking it out of the shoe. For the selected shoe, after putting the putty to fill the gap, the shoe is re-scanned.

For the chosen last (Fig. 4)), it is observed that if a shoe is made with this last, it will pinch near the toe and the outermost finger. The rear part of the shoe is open and usually the last does not need to be compared with the foot at the rear end once the size of the last matches that of the foot.

Having chosen the last, B-spline curves were fitted on the last (Fig. 5) and surfaces are created. The inbuilt function requires either a 3D curve or a curve on surface for each of the four boundaries. If the end point of a curve does not coincide with the beginning point of the next curve, this operation internally creates two new curves that meet at the midpoint of the line segment that joins the closest points of the two curves. Boundary conditions can be specified on the four boundaries. These can be position, tangent plane, implied tangent, or curvature continuity with another surface. Then the surface-point cloud difference for the foot and the last is calculated using the inbuilt functions (Fig. 6).

Finally, the last is modified interactively and the customized last is created (Fig. 7(a)). In this work, an innovative design of the shoe last has been proposed. The space in the shoe in front of the fingers has been done away with and a last conforming to the foot is prepared. The shoe fabricated in this way would be like linen wrapped over the foot with a hard sole. Fig. 7(b) shows the comparison of the CAD definitions of the foot, original last and the modified last. In the modified last, the foot is still seen jutting out, but assuming that the shoe is going to be stretchable, a judgment can be made by the user, while modifying the last and accordingly, the shoe can be customized.

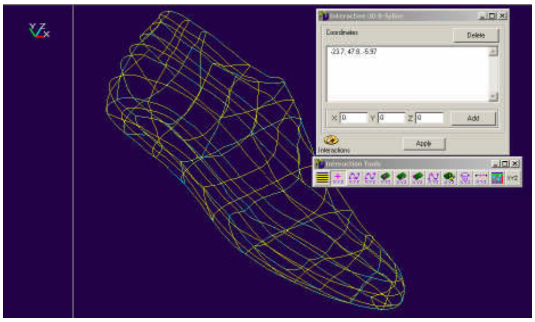

Fig. 5: Curves fitted over the shoe last using interactive 3D B-Splines.

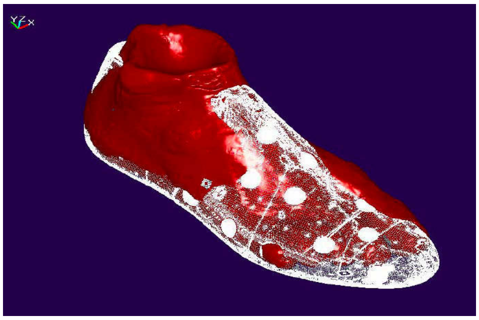

Fig. 6: Surface-point cloud difference for the foot and the last.

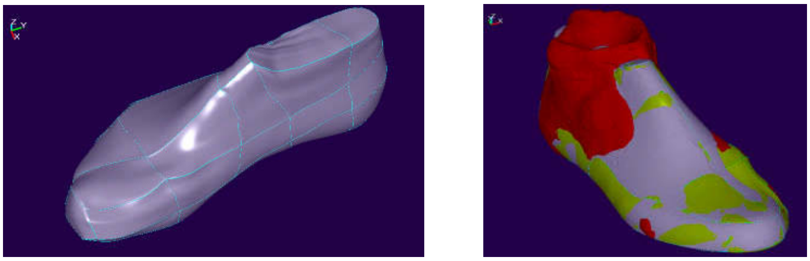

Fig. 7: (a) Modified shoe last, (b) comparison of original last, the foot and modified last.

4 RAPID PROTOTYPING OF CUSTOMIZED SHOE LAST

Prototyping is necessary for the conceptualization of any design. Rapid Prototyping (RP) saves time for generation of 3D models in addition to adding the accuracy which greatly reduces the investment in design phase by reducing the cost of production. After producing the CAD model of the customized shoe last, it is prototyped to produce the fitting shoe. The CAD model is converted to a neutral data (STL / IGES) format using Surfacer (Fig. 8) and imported into the Stratasys' software, Insight 4.2, for further processing. The RP process used is Fused Deposition Modeling (FDM) by Stratasys Inc. and the material used is Polycarbonate. Insight is used for slicing and layer deposition. Fig. 9 shows the support structure required for the shoe last. Post processing of the part is not required in this case as flat patterns of leather could be fitted over the rough surface too. For mass customization, CNC machining is preferred over RP process. The same CAD model serves as an input for CNC machining.

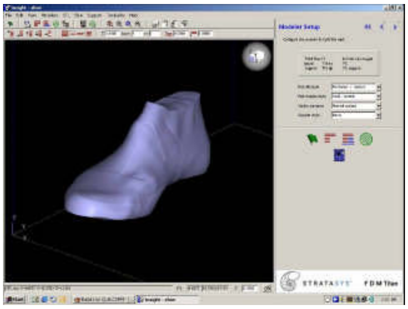

Fig. 8: STL file of the modified shoe last.

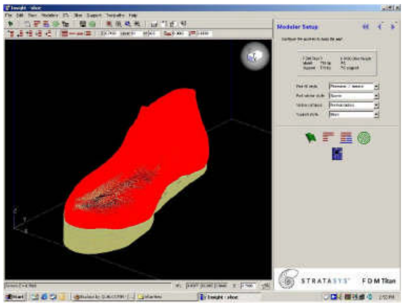

Fig. 9: Support Structure for the prototype.

5 CONCLUSIONS

This work presents a method to design and develop shoe lasts as per the customer needs. Customization has become the trend of the day in the production industry for all range of products, be they garments, footwear, jewelry, furniture, or any artistic object. Specialized software is being developed to deal with the design or prototyping of such products. Footwear is one area where there is lot of scope for innovation and designing; and the demand for it is growing. This work is a contribution in this area. The following conclusions can be drawn from the work:

(a). It is possible to use Computer Aided Designing for customization process effectively. Coupled with Reverse Engineering, it eliminates many of the intermediate processes in customization and reduces the time spent in the design and visualization phase.

(b). Shoe customization is one important area where there is scope for lot of research and development. The process needs to be made cheaper for making it more useful for the customers. The paper presents the mathematical approach to accomplish the job.

(c). The process can be highly effective to develop footwear for patients with podiatric disorders.

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