Designing a Tailored Shoe: Enabling Customization through a Computer-Aided Design (CAD) System

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***Abstract*— The shoe industry is a very competitive industry and in order to capture the market, customized shoes are desired nowadays to satisfy consumers' needs on style, fit and comfort. Companies need to either develop a system for quick design changes, creation of huge virtual design variations and in some cases adoption of mass-customization principles to reduce cost. Shoe-last is the "heart" of shoe making since it mainly determines the shoe shape, fashion, fit and comfort qualities. The concept of mass customization has become one of the key issues in the operations management theory and practice. Customers require an elevated variety of product choice while maintaining the sales price favorable. Therefore, manufacturers need to develop technologies and systems to deliver goods and services that meet individual customers' needs with low or even no price premiums charged. This is only possible if the manufacturing processes are organized with near mass production efficiency. This paper investigates the application of mass customization in the footwear industry and outlines the development and implementation of this concept. This study proposed a system to enable shoe- last design changes, exploration and eventually enable mass-customization. The system enables continuous change of styling and fashion to reflect personal taste without the need for physical design.**

Keywords: Feature Selection, Feature Extraction, Cad, Shoe Customization

I. INTRODUCTION

Previous studies have shown that ill-fitting shoes are the primary cause of various foot disorders. In the shoemaking industry, the shoe is categorized by the length (sometimes the length and width) for the customer to select. However, to select a pair of shoes to fit a person's feet, the fitting should include more than just foot length since different people have different foot shapes (wide vs. narrow; slim vs. fat; high-arched vs. low-arched), even though they may have the same foot length . Often, a customized shoe is needed, especially for the person whose foot shape is not normal. Additionally, there is a trend among the shoe manufacturers to advance the shoe customization so that the customers' satisfaction level and the manufacturer's competiveness can be improved. Therefore, there is a need of a system which can make customized shoes.

The shoe last, a solid mold around which a shoe is made, is the "heart" of shoemaking since it mainly determines the shoe shape, fashion, fit and comfort qualities. The back part of the shoe last is for fit and comfort while the toe part is mainly for fashion and style. Once the shoe last has been made, other shoe components (shoe upper, outsole, midsole, insole and the heel etc) can be made afterwards. Considering the great importance of the shoe last, this study focuses on the design of customized shoe last.[1]

In the traditional shoe manufacturing system, to make a pair of customized shoes is expensive, time-consuming and complicated due to constraints imposed by manual measuring of several dimensions of a specific foot and manual manufacturing of a shoe last to fit the specific foot dimensions through a trial-and-error approach .[2]

In recent years, with the rapid development of computer technology and advanced design and manufacturing technologies such as CAD/CAM, to automate the manufacturing process of customized shoe lasts becomes possible. The objective of this paper is to

propose a CAD system which can be used in shoe industries for shoe last customization.

II. BACKROUND

THERE HAS BEEN A GROWING TREND AMONG SHOE MANUFACTURERS TO INTRODUCE CUSTOMIZED SHOES TO SATISFY VARYING CUSTOMER STYLE, FIT, AND COMFORT NEEDS, THUS TO INCREASE THE PRODUCT'S ADDED VALUE. THIS STUDY PRESENTS A COMPUTER-AIDED DESIGN (CAD) SYSTEM FOR DESIGNING A CUSTOMIZED SHOE LAST BASED ON THE CHOSEN SHOE STYLE AND CUSTOMER'S FOOT FEATURES.

EIGHTEEN IMPORTANT FOOT FEATURES ARE

. THE FEATURES ARE THEN USED TO DEFORM THE BASE SHOE LAST OF THE CUSTOMER PREFERRED STYLE TO THE CUSTOMIZED SHOE LAST WITH BETTER FIT TO THE CUSTOMER'S FOOT, WHILE MAXIMALLY MAINTAINING THE CUSTOMER PREFERRED STYLE. FINALLY, THE FIT BETWEEN THE CUSTOMER'S FOOT AND THE CUSTOMIZED SHOE LAST IS EVALUATED THROUGH A COLOR-CODED MAP.[3]

III.METHODOLOGY

CAD TECHNOLOGY

Computer-aided design (CAD) is the use of computers (or workstations) to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing. CAD output is often in the form of electronic files for print, machining, or other manufacturing operations. The term CADD (for Computer Aided Design and Drafting) is also used.CAD may be used to design curves and figures in two-dimensional (2D) space; or curves, surfaces, and solids in three-dimensional (3D) space.[4]

CAD SYSTEM DESIGN

Since the shoe style/fashion is generally the first element that attracts customers and the good foot- shoe fit is very important for foot comfort and health, the primary aim of the CAD system is to design customized shoe lasts based on the customer preferred shoe style and his/her own foot features for good fit.[5]

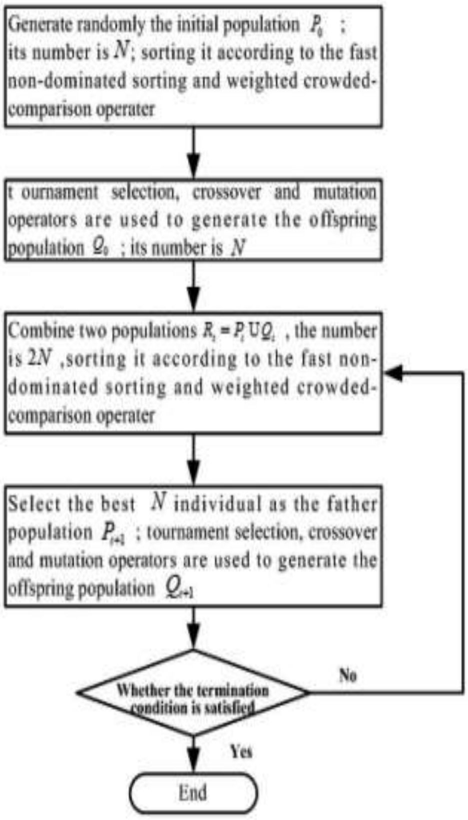


Figure 1: Framework Of Cad System For Shoe Customization Extracted From The Laser-Scanned Foot Data

To achieve aforementioned aim, the CAD system begins with the customer's selection of the preferred style (including color and shoe materials) from the huge digital database of shoes; at the same time, the customer's two feet will be laser scanned through a YETITM foot scanner within afew seconds. After two inputs from the customer (preferred style, laser scanned foot data) have been collected, the customer can leave the store and then the customized shoes will be delivered to his/ her mail address within a few weeks. Based on aforementioned two inputs, the CAD system will design the customized shoe last through the procedure shown in Figure 1. Visual C++ and OpenGL have been used for the development of CAD system and it consists of three main modules:[6]

(1) automatic extraction of 18 important foot features from the laser-scanned foot;

(2) a global grading together with the local deformation approach that can deform the base shoe last of the customer preferred style to the customized shoe last based on the extracted foot features, while maximally preserving the style of the base shoe last;

(3) a color-coded map for final evaluation of the fit/match between the customer's foot and the customized shoe last.[7]

IV. AUTOMATIC EXTRACTION OF FOOT FEATURES

After the customer has selected the shoe style from a digital shoe database, the base shoe last has been determined. However, the base shoe last probably does not fit the customer's foot in terms of both size and shape; thus, the base shoe last should be modified/reconstructed to match the customer's foot. In order to do this, the key features of that foot should be first extracted from the laser-scanned data, which consists of approximately 90,000 3D points distributed on the surface of an average foot (Chinese size 40). In this study, 18 key foot parameters (five lengths, four widths, three heights, six girths) have been identified from the design requirements for a customized shoe last; their definitions are given in Table 1. The 18 foot dimensions are primarily needed for characterizing the particular foot and reconstructing the customized shoe last later.[8]

FOOT SCAN

Since the automatic calculation of lengths, widths, and heights depends on the measuring axis, which can be affected by the customer's foot orientation during scanning, an automatic alignment is first applied on the scanned data to adjust the foot orientation to ensure consistency. This is done by letting the foot heel centerline be consistent with the scanner longitudinal axis through an alignment process similar to that used in Feng.[9]

Figure 2: Laser scan of the foot: the points are arranged in several parallel slices spacing by 1 mm

The process is described as follows:

Step 1: Select all scanned points no more than 25 mm above the bottom of the foot (XY plane, and project them on to the XY plane.

Step 2: Pick all projected points satisfying X 2 Xmin; 20% ðXmax XminÞ. Note that (Xmax − Xmin) is approximately foot length; hence, 20% × (Xmax − Xmin) corresponds to approximate 20% of the foot length from rear and thus can be considered as the foot heel region.

Step 3: Divide the aforementioned heel region into K (round to integer) sections; each section has a thickness of 1.1 mm, since the interval between each scanned slice from the laser scanner is around

1.0 mm

Step 4: For each section i (=1,2...K), find the two boundary points (point with minimum Y coordi- nate and point with maximum Y coordinate) and then determine the midpoint Ci.

Step 5: For the jth iteration, fit a least-square line Y= aj þ tan qj X from K midpoints Ci; the fitted line is considered as the temporary heel center line.

Step 6: If q 0:00175 (corresponding to 0.1°), go to step 8; else, rotate all the projected points by θj in a clockwise direction (if θj ≥ 0) or by −θj in an anticlockwise direction (if θj < 0) and store the coordinates of rotated points temporarily and then calculate angle θ from the equation θ = θ + θj (initial value of θ=0).

Step 7: Repeat steps 2–6 (j=j+1).[10]

Step 8: Rotate all the raw laser scan points (before projection) by cumulative angle θ in a clockwise direction (if θ≥0) or by −θ in an anticlockwise direction (if θ<0); now, the alignment process is completed.

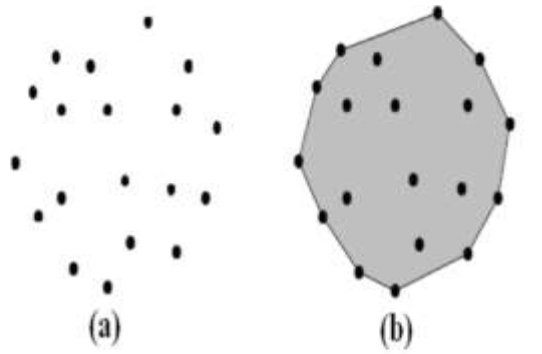


Figure 3: A point set (a) and its 2D convex hull (b) for

foot girth calculation

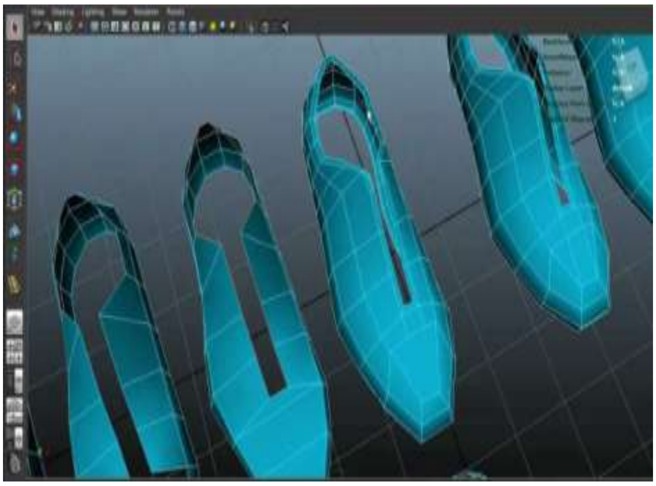


Figure 4: The fitted heel centerline in the jth iteration and its angle θj with X-axis

V. DETERMINATION OF FOOT PARAMETERS

Since the lengths, widths, and heights are all straight line measurements, the algorithms to determine them are quite straightforward and simple to implement based on their definitions; thus, their algorithms are omitted in this paper. Interested readers can refer to our previously published paper for the details. As to the girth measurements, we proposed to use a convex hull approach to take care of the non-uniform foot contours and to simulate the manual measuring procedure in shoe industry.

1. Locate the leftmost point (P1) and take it as the starting point.
2. Search through all the other points and find the point (P2) which has the largest angle (between upward vertical and vector P1–P2).
3. Based on the previous point Pi−1 and the current point Pi, find the next point Pi+1 from all remaining points including the starting point; Pi+1 makes the largest angle between vector Pi −Pi+1 and vector Pi–Pi−1.
4. Stop when the starting point is reached; else, go to step 3
5. Construct the convex hull using the points determined from steps 1 to 4.[11]

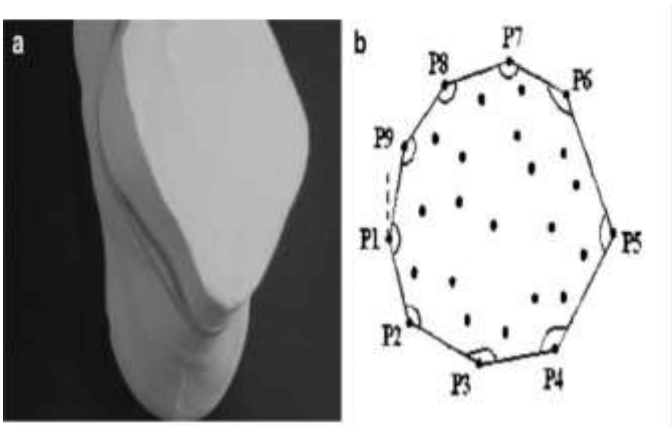


Figure 5: a) The manual measuring ankle girth with a cloth tape on the foot casting. b) The use of gift wrapping algorithm to generate a 2D convex hull to simulate the manual measuring procedure

VI. ALGORITHM VALIDATION

The proposed algorithms have been validated through an experiment on the right feet of 20 young healthy subjects (ten men, ten women). For each subject, two experienced foot measuring operators manually measured the aforementioned 18 foot dimensions twice. These four measurements are averaged and used as the reference to evaluate the aforementioned algorithms. Paired t test is used to statistically evaluate the differences between the automatic measurements from algorithms and the reference. The results showed that there are no significant ($P>0.05$) differences between reference (the averaged manual measurements) and automatic measurements on all 18 measurements except on the heel width. Additionally, the maximum differences on all measurements except long heel girth are within a few millimeters and acceptable for the practical applications in shoe last-making industry.[12]

Foot- Feature Based Shoe Customization

After successfully extracting 18 foot features (parameters), the design parameters for the ideal shoe last can be established based on the relationship between the foot and shoe last according to the national standard and the industrial guidance for shoe last design. The design parameters are then used to guide the reconstruction of the customized shoe last from the base shoe last. In order to maintain the customer’s chosen style which is mainly determined by the toe shape (pointed, rounded, squared, etc.), the shoe last reconstruction was done through a two-step approach: a global grading followed by a local deformation approach.

1. Global GradingFirst, a global grading is applied on the base shoe last to scale it in a certain ratio in order to minimize weighted differences between the ideal design parameters and shoe last parameters after scaling.

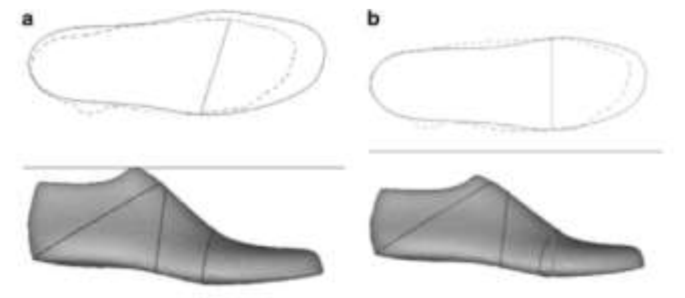


Figure 6: a) The base shoe last before global grading. b) After global grading (solid line denotes the shoe last, dotted line denotes the foot)

2. Interactive local deformation

The shoe last after global grading does not guarantee that all the regions on the shoe last match with the corresponding foot regions. Thus, a second step is required, named as the interactive local deformation, to achieve a good foot shoe fit in all regions. After the alignment of the scanned 3D foot and scaled shoe last by matching the heel centerline, non-uniform rational B-spline (NURBS), one of the most popular methods for designing complex surfaces in CAD and computer graphics, is applied to modify local regions/surfaces of the shoe last interactively by moving the control knots on NURBS surface.

Shoe Last Foot Fit Evaluation

Prior to the output of the digital customized shoe last to computer numerical control (CNC) processing for physical prototype, the final fit between the scanned foot and the customized shoe last should be evaluated. In this study, the dimensional difference of each point, defined as the shortest distance between the point on the shoe last and its nearest foot region along the norm of the last surface, is used to quantify the fit between foot and customized shoe last. Considering the same magnitude of tightness and looseness of the shoe last relative to the customer's foot can cause different levels of discomfort; the dimensional difference of each point has the sign (a −ve difference for tightness and a +ve difference for looseness) as well. All calculated dimensional differences are color-coded on the customized shoe last to provide the CAD system operator or the last designer with a clear picture showing the overall foot shoe last match or mismatch and to act as a guide if further local deformation is necessary. In cases where the mismatches in some shoe last regions exceed the specified tolerances, the local deformation should be further applied until all the dimensional differences are within the tolerated ranges. Once the color map shows that the shoe last fits the foot well, then the digital shoe last can be outputted to a computer numerical control machine for manufacturing the physical customized shoe last.[13]

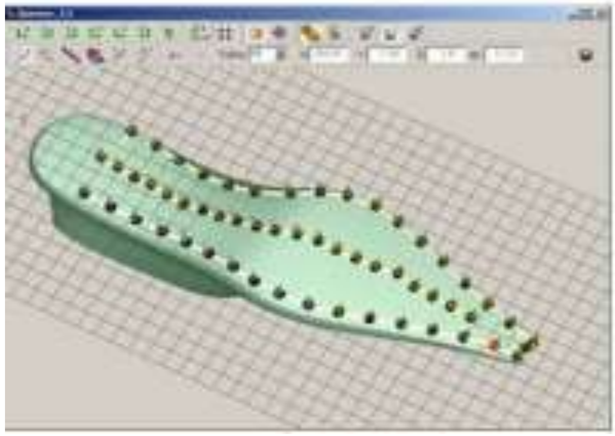
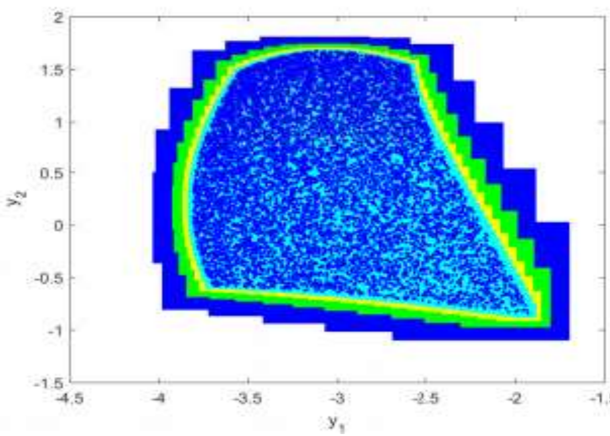


Figure 7: Interactive local deformation of scaled shoe last through NURBS surface. a) The shoe last before local deformation is tight to foot at foot dorsum, which is highlighted in the box. b) The control knob to modify the NURBS surface. c The shoe last after local deformation at dorsum

A. Multi-Layer Neural Networks A neural network consists of a number of interconnected neurons. Each neuron is a simple processing element that responds to the weighted inputs it received from other neurons. In this paper, we consider the most popular and general feed forward neural networks called the Multi-Layer Perceptron (MLP). [14]Generally, an MLP consists of three typical of layers: An input layer, that serves to pass the input vector to the network, hidden layers of computation neurons, and an output layer composed of at least a computation neuron to produce the output vector. The action of a neuron depends on its activation function, which is described as yi = f □Xn j=1 ωijxj + θi □ (1) where xj is the jth input of the ith neuron, ωij is the weight from the jth input to the ith neuron, θi is called the bias of the ith neuron, yi is the output of the ith neuron, f(·) is the activation function. The activation function is a nonlinear function describing the reaction of ith neuron with inputs xj (t), j = 1, · · · , n. Typical activation functions include rectified linear unit, logistic, tanh, exponential linear unit, linear functions, for instance. In this work, our approach aims at dealing with the most of activation functions regardless of their specific forms, only the following monotonic assumption needs to be satisfied. Assumption 1: For any x1 ≤ x2, the activation function satisfies f(x1) ≤ f(x2). Remark 1: Assumption 1 is a common property that can be satisfied by a variety of activation functions. For example, it is easy to verify that the most commonly used logistic function f(x) = 1/(1 + e −x) satisfies Assumption 1. An MLP has multiple layers, each layer

ℓ, $1 \le \ell \le L$, has $n^{[\ell]}$ neurons. In particular, layer $\ell = 0$ is used to denote the input layer and $n^{[0]}$ stands for the number of inputs in the rest of this paper, and $n^{[L]}$ stands for the last layer, that is the output layer. For a neuron i, $1 \le i \le n^{[\ell]}$ in layer ℓ, the corresponding input vector is denoted by $x^{[\ell]}$ and the weight matrix is $W^{[\ell]} = [\omega^{[\ell]}_1, \ldots, \omega^{[\ell]}_{n[\ell]}]^\top$, where $\omega^{[\ell]}_i$ is the weight vector. The bias vector for layer ℓ is $\theta^{[\ell]} = [\theta^{[\ell]}_1, \ldots, \theta^{[\ell]}_{n[\ell]}]^\top$. The output vector of layer ℓ can be expressed as $y^{[\ell]} = f_\ell(W^{[\ell]}x^{[\ell]} + \theta^{[\ell]})$ where $f_\ell(\cdot)$ is the activation function for layer ℓ. For an MLP, the output of $\ell-1$ layer is the input of ℓ layer. The mapping from the input $x^{[0]}$ of input layer to the output $y^{[L]}$ of output layer stands for the input-output relation of the MLP, denoted by $y^{[L]} = F(x^{[0]})$ (2) where $F(\cdot) , f_L \circ f_{L-1} \circ \cdots \circ f_1(\cdot)$. According to the Universal Approximation Theorem [26], it guarantees that, in principle, such an MLP in the form of (2), namely the function $F(\cdot)$, is able to approximate any nonlinear real-valued function. Despite the impressive ability of approximating functions, much complexities represent in predicting the output behaviors of an MLP. In most of real applications, an MLP is usually viewed as a black box to generate a desirable output with respect to a given input. However, regarding property verifications such as safety veri fication, it has been observed that even a well-trained neural network can react in unexpected and incorrect ways to even slight perturbations of their inputs, which could result in unsafe systems. Thus, the output reachable set estimation of an MLP, which is able to cover all possible values of outputs, is necessary for the safety verification of an MLP and draw a safe or unsafe conclusion for an MLP. B. Problem Formulation Given an input set X, the output reachable set of neural network (2) is stated by the following definition. Definition 1: Given an MLP in the form of (2) and an input set X, the output reachable set of (2) is defined as $Y , \{y^{[L]} \mid y^{[L]} = F(x^{[0]}), x^{[0]} \in X\}$. (3) Since MLPs are often large, nonlinear, and non-convex, it is extremely difficult to compute the exact output reachable set Y for an MLP. Rather than directly computing the exact output reachable set for an MLP, a more practical and feasible way is to derive an over-approximation of Y, which is called output reachable set estimation. Definition 2: A set $\tilde{Y}$ is called an output reachable set estimation of MLP (2), if $Y \subseteq \tilde{Y}$ holds, where Y is the output reachable set of MLP (2). Based on Definition 2, the problem of output reachable set estimation for an MLP is given as below. Problem 1: Given a bounded input set X and an MLP described by (2), how to find a set $\tilde{Y}$ such that $Y \subseteq \tilde{Y}$, and make the estimation set $\tilde{Y}$ as small as possible1 ?

In this work, we will focus on the safety verification for neural networks. The safety specification for outputs is expressed by a set defined in the output space, describing the safety requirement. Definition 3: Safety specification S of an MLP formalizes the safety requirements for output $y^{[L]}$ of MLP $y^{[L]} = F(x^{[0]})$, and is a predicate over output $y^{[L]}$ of MLP. The MLP is safe if and only if the following condition is satisfied: $Y \cap \neg S = \emptyset$ (4) where $\neg$ is the symbol for logical negation. Therefore, the safety verification problem for an MLP is stated as follows. Problem 2: Given a bounded input set X, an MLP in the form of (2) and a safety specification S, how to check if condition (4) is satisfied? Before ending this section, a lemma is presented to show that the safety verification of an MLP can be relaxed by checking with the over-approximation of the output reachable set. Lemma 1: Consider an MLP in the form of (2), an output reachable set estimation $Y \subseteq \tilde{Y}$ and a safety specification S, the MLP is safe if the following condition is satisfied $\tilde{Y} \cap \neg S = \emptyset$. (5) Proof: Since $Y \subseteq \tilde{Y}$, (5) directly leads to $Y \cap \neg S = \emptyset$. The proof is complete. Lemma 1 implies that it is sufficient to use the estimated output reachable set for the safety verification of an MLP, thus the solution of Problem 1 is also the key to solve Problem[15]



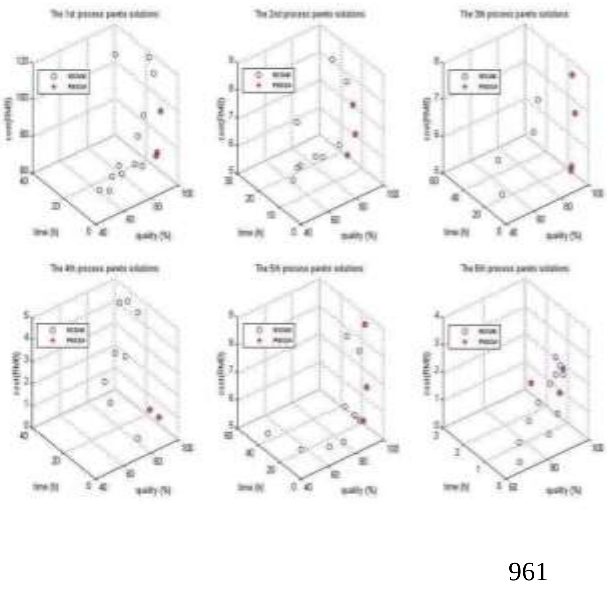


Figure 8: Simulation Result

VII. CONCLUSIONS

In this paper, a CAD system for shoe last customization has been proposed. The basic approach is to deform the base shoe last with the customer preferred style into the customized shoe last that fits the scanned foot data based on the customer's foot features, while maximally preserving the style of the base shoe last. With the continuous improvements on this CAD system, it has great potential to be applied into the shoemaking industry to design a pair of fashionable and well-fitting customized shoes for the customer in a short time with reasonable cost, thus achieving customer's high satisfaction level as well as manufacturer's commercial success.[8]

VIII. FUTURE SCOPE

It's future scope is that it can be created as a new emerging platform in fashion e-commerce as development of such application can enhance the customer satisfaction level which is required by every e-commerce brands and It's Image Processing algorithm can separately be a field of research as to come up with such good model which can predict human body dimension. Or, it can be used as a feature in every fashion e-commerce application to guide each customer with their best fit size as everyone have not same choice or body dimensions so they can get their custom-shoes at their doorstep.Due to the current situation of COVID-19 the application work not be not but we remain focused on doing the remaining part of it as soon as the situation gets well.

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