A Feature-based Shoe-last Design and its Automatic Model Construction Method in CAD Systems

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Abstract. This paper discusses the significance of shoe-last design in the shoe production process, emphasizing that the designs should be aligned with fashion trends and biomechanical requirements. Existing methods for customizing shoe lasts, whether traditional or digital, have limitations in efficiency and flexibility. To address these challenges, the paper proposes an automatic construction method for creating parametric CAD models of shoe-last structures. The proposed approach focuses on extracting intricate geometric features to realize automatic CAD model construction, aiming to improve the model construction efficiency and make the constructed models better editable for further modifications. The constructed models are compatible with Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM) systems for numerical simulation and manufacturing analysis. The goal is to streamline the design customization process, providing manufacturers with a more efficient and accessible solution while offering designers a user-friendly platform for creating personalized shoe-lasts.

Keywords: Design Automation, Automatic CAD Model Construction, Shoe-last Design, Feature-based, Parametric Modeling, Design Customization
DOI: https://doi.org/10.14733/cadaps.2025.600-615

1 INTRODUCTION

Shoe-last design is the most fundamental step of the shoe design process, and it is of critical importance for the final stage of shoe production. The success of a shoe manufacturer often hinges on the suitability of their initial shoe-last templates. Once a perfect shoe-last template is acquired, shoe companies typically refrain from easily replacing these last templates. This reluctance stems from the fact that even a slight alteration in a dimension on the last could result in a vastly different end-product experience for the user. However, the production of shoe-lasts heavily relies on the experience of cobblers, experiences that are challenging to parameterize. Even with the precision of modern 3D scanning technologies providing accurate foot models, deriving scientifically and

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comfortably fitting shoe-last models directly from specific formulas remains elusive. The trajectories of these surfaces are difficult to predict, and the curvature of these surfaces depends on the specifics of each foot. It is precisely due to the uniqueness of each foot that customized shoe-last production in the traditional shoe-making industry is highly inefficient and time-consuming. Given the scanned data of a specific foot, efficiently and scientifically processing this data, and translating it onto a customized shoe-last through an all-in-one system, has become paramount for mass customization of shoe-last.

A satisfying shoe-last design should not only align with the latest fashion trends in appearance but also meet the biomechanical requirements of a specific type of foot shape [2]. In the customization process of shoe-last, numerous data points need to be considered. The foot parameters that can be used include; foot length; longitudinal position of the arch, lateral ball position, medial ball position, first toe position and fifth toe position; foot width; lateral foot width; lateral arch width; heel width; ball girth; instep girth; toe height; ball height; and foot flare, medial foot width; toe width; lateral toe width; medial toe width [7]; Typically, cobblers manually measure these critical data points and handcraft suitable shoe lasts based on the scenarios for which the footwear is intended. Such crafted shoe-last suffice for the needs of the majority of individuals in their everyday wear. However, for many individuals with unique foot shapes, particularly adolescents in their developmental stages and elderly individuals with relatively fragile bones, these standard shoe lasts can easily cause significant harm to their feet. Many people wear ill-fitting shoes every day due to the uniqueness of their foot shape, leading to foot fatigue, damage, or even disabilities [3]. Typically, cobblers manually measure these critical data points and handcraft suitable shoe lasts based on the scenarios for which the footwear is intended. Such crafted shoe-last suffice for the needs of the majority of individuals in their everyday wear. However, for many individuals with unique foot shapes, particularly adolescents in their developmental stages and elderly individuals with relatively fragile bones, these standard shoe lasts can easily cause significant harm to their feet. Therefore, design customization of a shoe last based on a specific foot feature is important for its wearer, especially for individuals with special foot shapes. Both traditional methods of crafting and CAD feature modeling pose numerous challenges when it comes to customizing shoe-last for individuals with special foot shapes. While manual craftsmanship allows for the modification of existing shoe-last models based on measurements of unique foot shapes, this approach is uneconomical and inefficient. It is not feasible for ordinary individuals to afford, and even skilled cobblers may struggle to achieve this objective. The process of manually adjusting shoe-last entails significant learning curves and relies heavily on experience. Furthermore, due to the lack of experience and the vast differences in individual foot shapes, manually measured and adjusted shoe-last may not effectively fulfill their function of protecting the feet.

Obtaining a specialized shoe-last model through CAD feature modeling also presents numerous challenges. The complexity arises from the intricate nature of human foot feature data and the lack of straightforward conversion methods between foot and shoe-last parameters, making it difficult to create new CAD models based on obtained foot parameters. Furthermore, in the design process of shoe-last models, the interdependencies among various data points of the shoe-last model pose challenges to modifying the entire shoe-last model by adjusting one or a few data points. Even with a foundational feature model containing numerous parameters, the volume of data required during the process of re-measuring foot data can be substantial. Mere alterations to a few parameters often prove insufficient for model recreation. Moreover, the shoe-last production process involves two separate entities: one for data measurement and another for model modification based on this data. Collaboration between these entities may be challenging as the department responsible for measurements may lack modeling expertise, while the entity familiar with modeling may struggle with measurements. To ensure the economic viability and production efficiency of customizing specialized shoe-last, we require an all-in-one system. This system should enable professional and efficient shoe-last customization based on users' foot shapes, even without the operator's familiarity with CAD modeling or specialized foot data knowledge.

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2 LITERATURE REVIEW

There are various methods to customize shoe lasts. In the traditional custom shoe industry, shoemakers manually measure data and customize shoe lasts by polishing wooden lasts based on their experience [8]. With the rapid development of computer technology, CAD/CAM has been widely applied in the footwear industry, which significantly improves the overall efficiency of its design and production [18]. Shi et al. [13] extracted 18 parameters from the human foot and compared those parameters on the standard shoe-last. NURBS (Non-Uniform Rational B-spline) is applied to the last deformation. Leng et al. [6] also designed a CAD system to deform the foot to the last. They used a distance map to allocate the difference between the sample points on the surface of the scanned foot model and the shoe-last model. Wang et al. [16] utilized a multi-layer parametric definition (MLPD) to address the features of shoe-last. They used five types of proper constraints to control the surface of the shoe-last model, to re-model the shoe-last model. Mishra et al. [9] developed a new 3D design process for customizing shoe-last aiming to have better comfort and designed shoe-last. Sambhav et al. [12] used the point cloud to convert foot data to the last. By selecting the right size and foot shape, an S-spline is applied to generate the shoe-last model.

The current digital shoe-last modeling method consists of 3 main steps. First, feet data is acquired with 3D scanning technologies, where customers' feet are scanned by laser scanning systems, and the obtained 3D data is postprocessed and stored either in a feature template [11] or in a discrete point cloud format [17]. Subsequently, a 3D feet model is constructed in a 3D modeling software based on the acquired data. Then, the main relationships between foot shape and shoe-last shape are studied, and a foundational shoe last similar to the customer's foot shape is obtained [1]. The pivotal role of shoe-last design cannot be overstated in the intricate process of shoe manufacturing. Indeed, it serves as the foundation upon which the entire shoe production process rests. The efficacy of a shoe manufacturer often hinges on the suitability of their initial shoe-last templates, recognizing that even the slightest alteration in dimension could yield vastly different end-product experiences for the user. However, the production of these critical templates heavily relies on the experiential knowledge of cobblers, whose insights are challenging to systematize. Despite the precision afforded by modern 3D scanning technologies in providing accurate foot models, the direct derivation of scientifically and comfortably fitting shoe-last models from specific formulas remains elusive. The trajectories of these surfaces defy simple prediction, with the curvature contingent upon the unique characteristics of each foot. Consequently, the traditional shoemaking industry grapples with inefficiencies and time-consuming processes in the customized production of shoe-last, exacerbated by the inherent uncertainty in foot data. In light of these challenges, the imperative to efficiently and scientifically process foot data and translate it onto shoe-lasts through an integrated system has become increasingly paramount, particularly in the context of mass customization. This necessitates a paradigm shift towards leveraging digital tools and virtual environments in shoe-last design, albeit with due regard for the preservation of venerable craftsmanship. The fusion of traditional expertise with emergent technologies presents a pathway toward innovation and efficiency, albeit one requiring concerted efforts in training and educational initiatives. In essence, while the existing shoe-last modeling method lays the groundwork for precision and accuracy, its limitations underscore the urgency for continual refinement and innovation to meet the evolving demands of footwear design and manufacturing.

This paper introduces a method for automatically constructing a parametric CAD model of a shoe-last structure based on features. Our primary focus lies within the demographic of individuals undergoing development, those with foot deformities or injuries, and the elderly population. These cohorts exhibit relatively fragile foot structures, thereby necessitating greater flexibility and accommodation within footwear designs. For instance, elderly individuals with high arches may not prioritize footwear performance, but ill-fitting shoes can significantly impact their skeletal health. Thus, while ensuring proper fit remains paramount, providing ample space in the shoe upper becomes imperative for such demographics. Additionally, for individuals with long-term foot deformities like hallux valgus (large dispersions of HVA values [3]), optimizing the width of the shoe sole is crucial to ensure a snug fit to their foot contours. Importantly, data about the foot

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characteristics of individuals with hallux valgus does not deviate significantly from those utilizing standard shoe-last of similar foot length in other dimensions. Consequently, there is an urgent need for research into a shoe-last customization method that is rapid, precise, and universally applicable to cater to the diverse needs of these populations. The primary objectives of this proposed method are to improve the CAD modeling efficiency of intricate geometric structures as well as improve the editability of the constructed model. The target structures can be characterized by parameterized and spatially repetitive features. For example, a shoe-last can be parameterized and may have spatial repetitive characteristics across various human foot shapes. The automatically constructed CAD model is parametric, allowing for the easy further editing of design parameters for each shoe-last model. Moreover, the model is compatible with CAE and CAM systems for numerical simulation and manufacturing analysis.

3 CONCEPTUAL FRAMEWORK OF THE PROPOSED SHOE-LAST DESIGN PROCESS

The suggested method for automatic CAD model construction for a customized shoe-last comprises three sub-steps, as illustrated in the flow chart depicted in Figure 1. Initially, a 3D foot scanner is employed to capture foot data from the experimental subject (customer). The foot scanner is fast, reliable, and simple and creates a 2.5D scan with the relevant measures of the foot [10]. The 3D scanner we chose is a UCS foot scanner. This machine is commonly used in the shoe design industry. Subsequently, the material distribution structure data is reformatted, and a dedicated file is generated to store this information. In the second step, the shoe-last structure elements, sourced from diverse shoe-last models, are categorized into various subtypes based on their geometric characteristics. These elements are appropriately parameterized, encapsulated, and integrated. Lastly, a CAD system plug-in is developed to read the data file and facilitate the automatic construction of the CAD model.

3.1 Feet Data Acquisition, Model Data Representation, and Data File Creation

In this section, we present a fresh mapping correlation linking the standard shoe-last model's geometry and the data obtained from scanning human feet (see Figure 2). The updated data format builds upon conventional data representation, incorporating additional information to enhance design flexibility.

In the traditional shoe-last production process, 3D scanning is used to create shoe-last models. The process involves precise scanning and measurement, digital management and modification of lasts, and 3D printing. This approach allows for the production of footwear that is tailored to individual foot shapes and sizes, ensuring better fit and comfort. However, the relevant method of manufacturing shoe-lasts is mainly based on experience, which usually has low efficiency. In addition, ordinary users find it challenging to obtain such services. Moreover, the adaptability of shoe-lasts is not entirely satisfactory.

In this article, we will provide a detailed introduction to the functionality of the CAD system plug-in. Firstly, we will outline the data structure and sequence required from users, as well as the interface design of the CAD system plug-in. This stage is crucial for achieving human-computer interaction. A user-friendly software design is essential for widespread usability. A straightforward operating environment also breaks down technical barriers between shoe-last designers unfamiliar with modeling and CAD software engineers unfamiliar with shoe-making techniques. Next, we will explain how we handle user foot data. This data is sourced from files obtained by 3D scanners scanning the user's feet. In this step, the INFOOT 3D foot scanner (see Figure 3) was used to obtain the scanned feet data. The INFOOT 3D Foot Scanner is a non-contact scanner designed to capture the precise shape and anatomical measurements of the human foot. This scanner is widely used in custom shoe-last creation and orthotics due to its high accuracy and efficiency.

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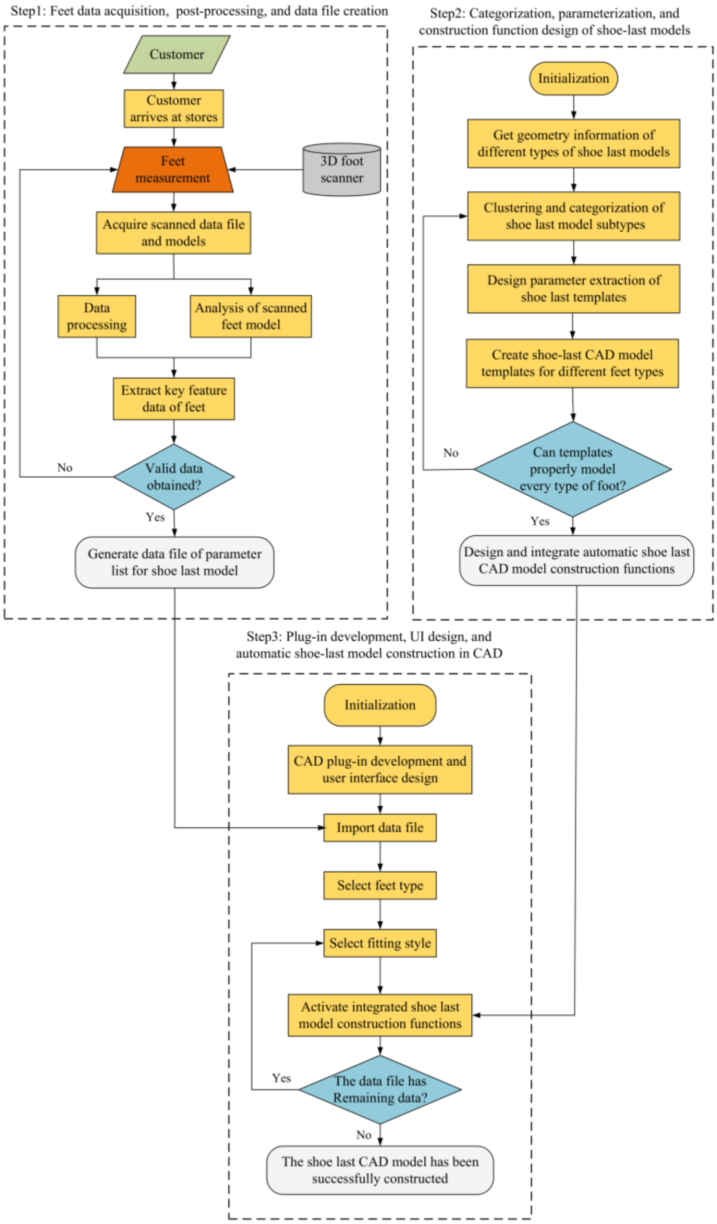

Figure 1: Flow chart of the proposed method framework.

After getting the data file, we need to process it to extract useful data, match it with standard shoe last models in the library, optimize its feature data, and generate new data matching the user's foot shape. Finally, the system will refit this new data, progressing from points to lines, then from lines to surfaces, generating new shoe-last surfaces based on the user's foot shape. The entire process will be validated through a case study, where we will present a complete process from scanning foot features in 3D to generating customized shoe-last models. Figure 4 is the UML class diagram for this stage.

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Figure 2: 3D-scanned model of the human foot.

Figure 3: INFOOT 3D Foot Scanner for feet data acquisition.

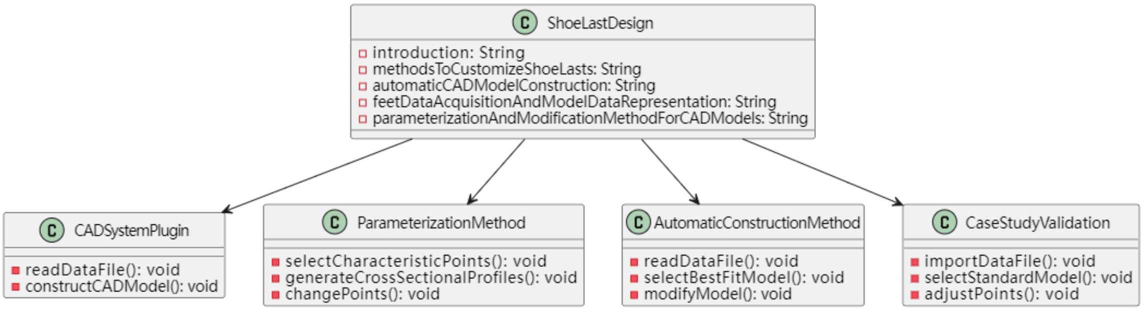

Figure 4: UML diagram for shoe-last auto-customized design process.

4 FEATURE-BASED AUTOMATIC SHOE-LAST MODEL CONSTRUCTION

In our proposed method, the scanned feet data is post-processed, and additional information is incorporated into a new data file. The additional information can either be extracted from the scanned feet data or provided by customers' requirements, such as foot length, width, fit type, and arch height. The proposed new data file format can be directly read by CAD software and helps to select a best-fit shoe-last model candidate from the standard size-based library.

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4.1 CAD System Plug-in UI Design

In the UI design of this automatic shoe-last design, we have broken down the customization process into three parts: scanned data input, shoe-last model selection, and shoe-last model modification. Throughout the entire interaction between the UI and the user, our operations are highly user-friendly. Even users unfamiliar with the principles behind our automatic customization of shoe lasts can navigate the process smoothly.

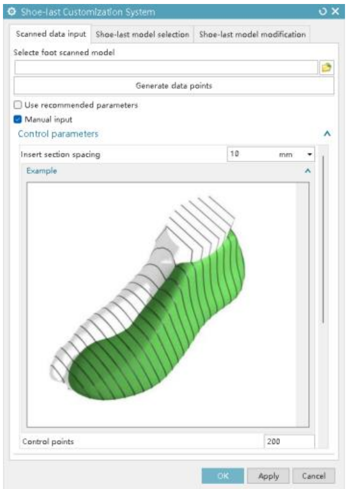

Figure 5: UI design for CAD model plug-in.

During the process of generating feature sections and feature points, we offer users two options: “Use recommended parameters” and “Manual input” (see Figure 5). Here, inserting sections at smaller intervals and increasing the number of control points on each section leads to greater computational requirements for model optimization. Consequently, the accuracy of the optimized shoe-last also increases. However, higher computational requirements do not always result in the best user experience. Instead, they may significantly increase the time required to generate the optimized model, with little difference observed between the models generated using higher computational resources and those using recommended parameters. Therefore, for ordinary users, selecting “Use recommended parameters” would be the preferable choice.

Upon uploading the 3D scanned files and inputting reference data controlling the precision of the optimization model, our CAD plug-in proceeds to further process this data. Based on the user’s input 3D scan model file, the system automatically matches the most similar standard shoe-last model from our library. Our library contains standard shoe-last models ranging from US size 5 to US size 13. Under each directory of the same foot length, there are nine different derived models corresponding to different arch heights and foot widths for the same shoe size. Each shoe size also offers three different templates for foot width: Thin, Standard, and Wide, as well as three options for arch height: Low, Standard, and High. During the process of matching the standard model to be optimized, users can already manually input data through the “manual input” option (see Figure 6). For users who have made initial judgments about their foot shape, this feature reduces the time required for model matching and yields more precise optimized models.

The interaction between our CAD plug-in system and users is illustrated in Figure 7, where users can see how their foot feature data is transmitted from the 3D foot scanner to our shoe-last model library.

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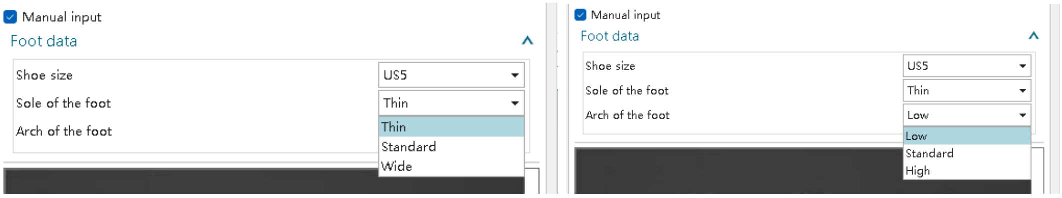


Figure 6: Parameters' manual input for the standard shoe-last model selection.

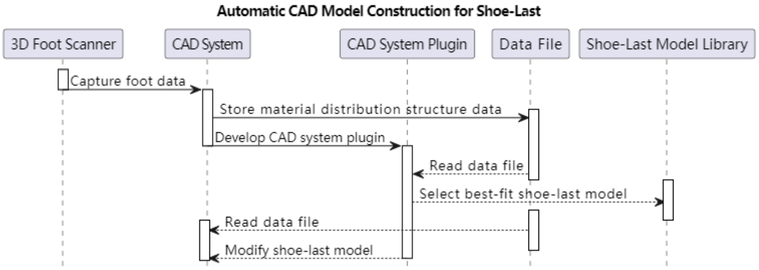
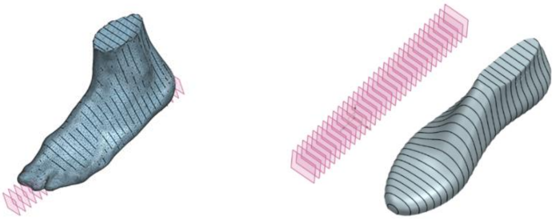


Figure 7: UML sequence diagram for shoe-last automatic CAD model construction.

4.2 Parameterization and Modification Method for Shoe-last CAD Models

Here, we propose a method to dynamically parameterize and modify the selected shoe-last candidate model according to the 3D-scanned foot data/model, aiming to obtain a better-fitted customized shoe-last. This approach involves selecting characteristic points on the 3D-scanned foot surface by generating reference planes. N cross-sectional profiles are generated, and the overlapping regions with the scanned foot model result in N intersecting sectional lines (see Figure 8(a)). Simultaneously, using our defined *CreateSectionCurve()* function, we could get N cross-sectional profiles spaced at equal intervals, intersections with the standard shoe-last model of the same size as the scanned foot model are obtained, yielding N sectional lines intersecting with the standard shoe last model (see Figure 8(b)).



(a) (b)

Figure 8: N sections intersect with the model to obtain the section curve diagram: (a) N sectional lines intersecting with the human foot model, and (b) N sectional lines intersecting with the standard shoe last model.

On each of these N cross-sections, using our defined *CreateCurvePoint()* function, M characteristic points can be obtained and selected sequentially from the 3D-scanned foot model. Then, the corresponding M characteristic points are obtained in the candidate standard shoe-last model on the same cross-section. The details of selecting M control points in our proposed method are described below. First, the centroid of each cross-section is calculated and determined as the "center point." Next, starting from this center point, a ray along the positive Y-axis direction is released. The

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intersection point of the ray and the cross-section is defined as the first control point. Then, the ray is rotated clockwise with an angle of 360/M degrees, and the new intersection point is obtained as the second control point. Finally, the ray rotation process is repeated M-1 times, which yields M control points sequentially. The N and M determine the spacing between cross-sections and the distance between the two nearest characteristic points in a cross-section. The selection of N and M depends on the desired precision for generating the corresponding shoe-last model. As N and M increase, the required computation time for optimizing the model will increase. Typically, a cross-section spacing of 10 mm and 200 characteristic points on each cross-section are sufficient to obtain accurate shoe-last models based on different foot shapes. As shown in Figure 9, we observe that some characteristic points in the cross-sectional image of the 3D-scanned foot model are located outside the cross-sectional image of the standard shoe-last. This indicates that certain dimensions of the feet in our study sample are wider than the standard shoe-last size, and proper modifications of the original standard shoe-last model are needed.

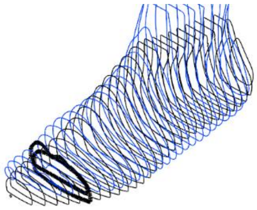

Figure 9: Comparison of the characteristic points on the human foot cross-section (blue) and the cross-sectional characteristic points on the standard shoe-last model (black).

By using our defined *ChangePoint()* function, an automatic point-by-point assessment and modification algorithm is implemented. This function traverses through all cross-sectional feature points of the 3D scanned foot models and the related two nearest feature points from the standard last candidate model. If the assessment indicates that the feature points of the scanned model are outside the cross-sectional line of the last candidate model, these two last model feature points will be displaced outward (along the direction from the cross-sectional center to the feature point location) with an offset value. This process will be repeated until the point lies within the cross-section of the last models. With this method, it can be ensured that each characteristic point of the 3D scanned foot model lies within the cross-section of the modified shoe-last model. Complete coverage of the automatically modified shoe-last cross-sectional area with the cross-section of the related 3D-scanned foot model can be realized by looping over the M characteristic points along the cross-sectional line (see Figure 10). This process is repeated for each of the N cross-sections.

In Siemens NX, the user can set continuity constraints from the UI of contour-based surface reconstruction. In our case, the built-in G2 continuity (also known as curvature continuity) constraint with proper tolerance is set to reconstruct the shoe-last surface that traverses all boundaries, ensuring curvature continuity and surface smoothness at the inserted cross-sections. With the data from the modified shoe last on N cross-sections, we define and use *BuildShoeLast()* function and employ the Curve Set (G2) functionality to create a new shoe last model.

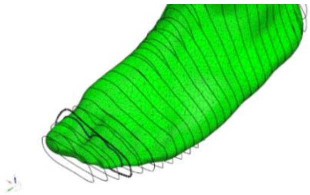

Figure 10: Characteristic points on the adjusted shoe-last section.

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4.3 Automatic CAD Model Construction

A plug-in is developed in a CAD system to realize automatic shoe last model construction for design customization. The created data file can be directly read with the designed user interface (UI). With the shoe size and foot type information, a best-fit shoe-last model candidate is selected from the standard library, and scanned foot data is used to modify the model automatically. A traverse algorithm is designed for the CAD system to read each line of the data file. While reading each line, the *CreateSectionCurve()* function is activated with the inputs from the current line of the data, and *CreateCurvePoint()* function is activated to obtain all characteristic points from the scanned foot model. Then, *ChangePoint()* function is used to change all characteristic points for the shoe-last. While reading each cross-section grouped by characteristic points, the *BuildShoeLast()* function is activated with the inputs as the new curves, and a customized parameterized shoe-last model is constructed automatically.

In our proposed approach, additional information is incorporated and retained. The storage consumption of the constructed model increases due to the inclusion of a greater number of design parameters. Nevertheless, the resultant model is more precise and characterized as a feature-based parametric model, exhibiting enhanced compatibility, editability, and design flexibility.

5 CASE STUDY

In this section, the proposed method is validated with an automatic customized shoe-last model construction in a widely used 3D CAD software, Siemens NX. A group of US 10-sized feet with wide foot shapes and high foot arches is used as the case study. The scanned data files are listed below (see Figure 11).

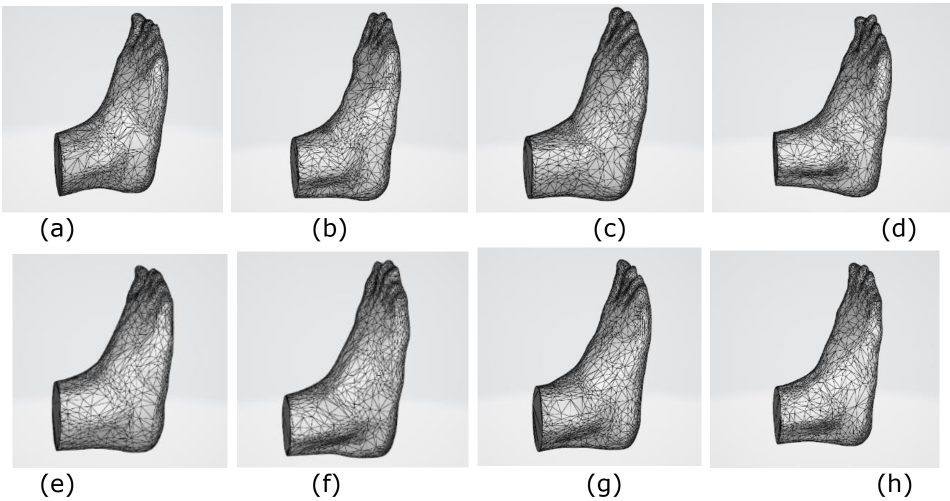

Figure 11: 3D scanned foot model for US 10-sized feet.

The average foot length of users with diverse foot shapes in the 3D scan models was 282 mm, with users typically purchasing US-size 10 shoes. Upon importing the data file, a standard shoe-last model of the same size (US 10, 280 mm) was selected from the library. A noticeable discrepancy was observed in the forefoot region between the foot feature model and the standard shoe-last model (refer to Figure 7(a)). In configuring the plugin settings, “Insert section spacing” was set to 10 mm, and “Control points” to 200. Following input of these initial parameters, the plugin processed the selected 3D scan foot model. Input values on the plugin interface are depicted in Figure 12.

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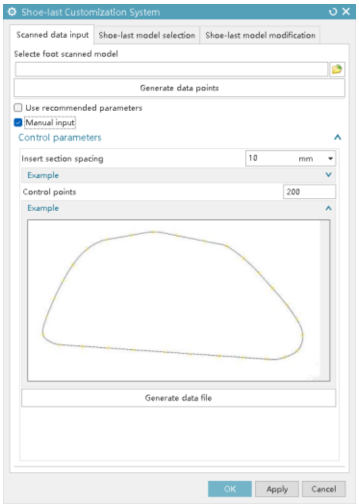

Figure 12: User input for cross-section spacing and control points amount.

Users unfamiliar with these parameters may opt for "Use recommended parameters" to extract data from their scanned foot models. For each user's foot model, cross-sections were inserted at 10 mm intervals along the X-axis, yielding 28 cross-sections. At each intersection, 200 feature points were extracted. The same methodology was applied to obtain cross-sectional lines and feature points for the corresponding standard shoe-last model.

When matching the last templates, users are presented with two options: "Auto pick from library" or manual selection. With the former, the system automatically determines the user's foot length based on the number of inserted cross-sections in the 3D foot model file, subsequently selecting the appropriate shoe-last size. Next, the system compares the coordinates of the 5th feature point on the foot model's cross-section to ascertain the user's foot type (see Figure 13). Comparisons are made between the maximum and minimum coordinates of the foot width on the 5th cross-section of the 3D scan model and the corresponding standard shoe-last model. As we can see from the picture, the lateral part of the scanned user's foot cross-section line (yellow) will be narrower than the cross-section line of the standard shoe-last (black). How to adjust this gap will be the key to controlling the overall shape of the adjusted shoe-last. We must not only ensure the smooth surface of the shoe-last model without destroying the shape of the shoe-last model but also reasonably adjust the selected standard shoe-last cross-section line based on the difference between the two cross-section lines. Therefore, we compare the distance between the corresponding feature points with the same number on the two sections with the tolerance distance we set in advance to determine whether the target feature point needs to be moved. Of course, if the feature point data on this section is too different, we will directly give up modifying the shoe last model of the standard foot type, and then go to our library to retrieve a shoe last model that is more suitable for the user's foot type. Under the same foot length conditions, our library also has shoe-last model templates for various combinations of high and low arches or wide and narrow soles. If the absolute difference in foot width exceeds 10 mm, the system categorizes the user as having wide feet; otherwise, the user is categorized as having narrow feet. A similar comparison is made for the height of the foot arch; if the difference exceeds 6 mm, the system determines whether a high-arch or low-arch shoe-last template is required. If the absolute difference falls within 6 mm, the system adjusts to a standard arch height shoe-last model. Users with knowledge of their foot characteristics can manually input their data to obtain a shoe-last template that best matches their foot type. Figure 14 illustrates the data input options available to users for selecting the most suitable shoe-last template. Utilizing our proposed algorithm, points extracted from the standard shoe-last model outside the scan model's cross-sections were automatically adjusted to generate a new shoe-last cross-sectional curve.

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Notably, within the same cross-section, users with wider forefeet exhibited significant widening along the X-axis compared to the standard shoe-last model, while differences along the Y-axis were minimal.

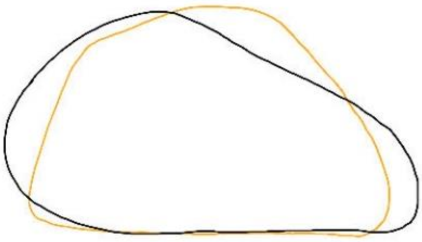

Figure 13: Comparison of the cross-section for the scanned foot model and standard shoe-last model (yellow line is scanned foot model; black line is the standard shoe-last model).

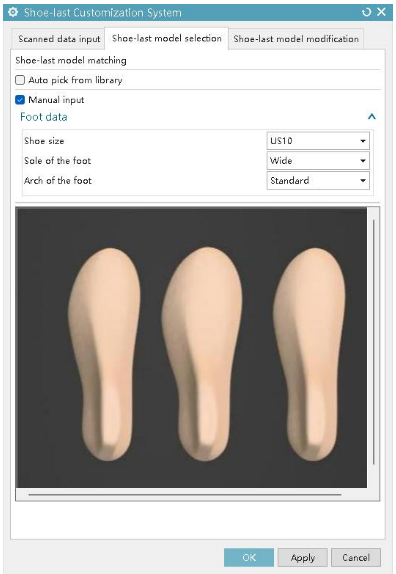

Figure 14: Shoe-last model selection from the library.

Once our CAD plug-in system completes the optimization of all feature points on each selected feature section, we employ the surface generation (G2 continuous) functionality inherent in SIEMENS NX 12 to optimize the shoe-last template intelligently. G2 continuous (also known as curvature continuous) generates complete and smooth reflections crossing all boundaries. Curvature continuity implies that along the boundary of any surface, there is the same radius of curvature at any "point." Products requiring high-quality appearance demand G2 continuous curvature. Through this feature in NX, we obtain the optimized new shoe-last surface. A new surface was formed through curve stitching (see Figure 15(a) and Figure 15(b)), and it is evident that the newly generated shoe-last forefoot is significantly wider, providing a dimension that better conforms to the user's foot shape.

Figure 16 illustrates a comparison between the user's 3D scanned foot model (in gray) and the standard shoe-last model called from the library (in green). Through experience, we can observe that the user's foot width is wider than the standard model in the library, while the arch height is slightly lower. This comparison graph effectively demonstrates the dilemma faced by ordinary users

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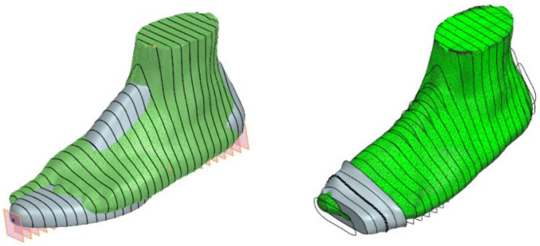
when using shoes made from standard shoe lasts: shoes are either too narrow or press against the instep when selecting the correct size, making it difficult to find a pair that fits both foot width and arch height perfectly. However, after optimization with our software, Figure 17 shows a comparison between the optimized shoe-last (in green) and the standard shoe-last called from the library. The width of each constructive cross-section of the shoe last models before and after optimization has been measured, compared, and analyzed together with the scanned feet model. Based on cross-sectional geometric analysis, it is found that the optimized shoe-last has a wider width but a slightly lower arch height than the template shoe-last, which provides a better fit for the user's foot feature. These adjustments do not compromise the user's wearing experience; instead, they enhance shoe comfort and better conform to the user's foot shape. From the user's input of the 3D scanned foot model to the generation of the optimized shoe-last model by the CAD plug-in, the entire process takes no more than five minutes. The introduction of this system significantly reduces the time required to customize shoe-lasts and lowers the customization barrier.



(a) (b)

Figure 15: An automatically constructed customized shoe last model: Comparison of US 10 wider foot (green) and US 10 standard shoe-last (concrete); (b) An automatically constructed customized shoe-last model with wider forefoot region.

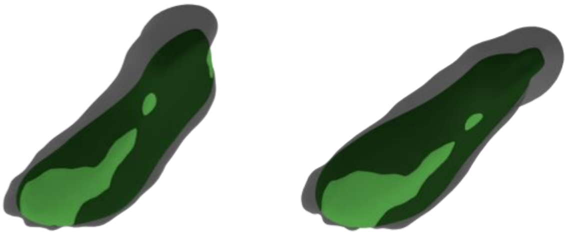


Figure 16: Comparison of user's foot scanned model with the standard shoe-last model in the library.

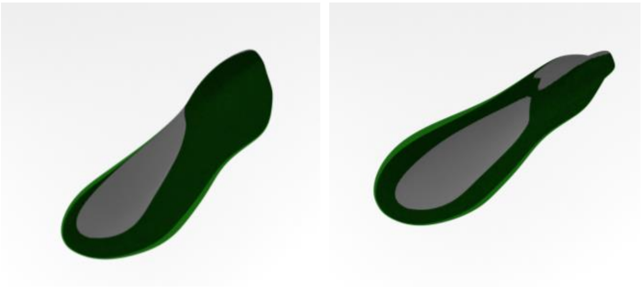


Figure 17: Comparison of modified shoe-last model with the standard model in the library.

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6 CONCLUSION AND FUTURE DEVELOPING OUTLOOK

So far, our developed CAD plug-in for automatic customized shoe-last can cater to individuals with relatively unique foot widths and instep heights. However, there are still many types of special foot shapes to consider. For instance, many patients suffer from flat feet [15], a condition characterized by the flattening of the medial arch. To provide more effective customization for users with foot deformities or injuries, it is evident that the current algorithms are insufficient. Moreover, from the perspective of athletic shoe production, obtaining customized shoe lasts is just the first step in customization. Shoemakers still need to craft special shoe-upper materials based on these customized shoe-last models. This process may involve 3D printing, followed by manual cutting of fabric to create fitted shoe upper materials. This additional step significantly increases both the threshold and time required for custom shoe production. A truly comprehensive customization process for footwear should achieve seamless design and processing in a single step. Therefore, in future research, we need to focus on reverse-engineering shoe upper patterns directly from obtained customized shoe last models. Additionally, careful consideration must be given to the customization process for insoles, ensuring that the entire shoe perfectly conforms to the user's foot shape, thus facilitating use for a wider range of foot disease patients. In terms of correcting feature points, we can refer to the method of utilizing piecewise cubic rational Bezier curves to approximate these boundaries, thereby extracting feature boundaries from 3D point cloud data and reconstructing CAD models more effectively [14]. Additionally, we can reconstruct 3D surfaces by slicing the point cloud into cross-sections and deriving curve patches to describe each section, utilizing properties of convex hulls and Voronoi diagrams [5]. This approach minimizes human intervention while efficiently extracting local features and reconstructing the global object morphology.

Through the exploration and research outlined in this paper, we have introduced an automated method for constructing customized shoe-last models, aiming to address the inefficiencies and limitations present in traditional shoe-last production processes. Our method encompasses the entire process from foot data acquisition to CAD model construction, facilitated by the development of a CAD system plug-in. The plug-in, characterized by its user-friendly interface, efficiently processes user-provided foot data and automatically adjusts standard shoe-last models according to user requirements, thereby achieving improved fit and comfort.

In the validation phase through a case study, we successfully demonstrated the effectiveness of our method in practical applications. Utilizing widely-used 3D CAD software, we scanned a group of users with diverse foot shapes and showcased the automated customization process, resulting in shoe-last models better suited to individual users' feet. By adjusting the dimensions and shapes of standard shoe-last models, we achieved a better match with users' actual foot shapes, thus enhancing comfort and wear experience.

Nevertheless, despite the significant progress made by our method, challenges and areas for improvement remain. Future research directions include enhancing the capability to apply adjustments on the shoe-last model, which allows for unrestricted transformations by enabling users to apply deformations using arbitrary reference points. This flexibility supports refining local details or correcting surface flaws with high precision [4]. Also, further optimization for users with foot deformities or injuries, as well as exploring methods for reverse-engineering shoe upper patterns directly from customized shoe-last models. Additionally, for customized athletic shoe production, attention must be paid to the customization process for shoe upper materials to achieve comprehensive customization goals.

In conclusion, this study provides valuable insights and methods for the development of customized shoe-last models, laying the groundwork for broader customization in footwear production. By integrating advanced technologies with user needs, we believe that automated methods for customizing shoe-last models will bring greater benefits and development opportunities to the footwear industry.

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ACKNOWLEDGEMENTS

The authors would like to acknowledge Siemens NX for providing student licenses.

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