Title:
A Feature-based Automatic Model Construction Method in CAD for Shoe-last Design

Authors:
Hengxu Li, hengxu@ualberta.ca, University of Alberta
Tianyu Zhou, tzhou4@ualberta.ca, University of Alberta
Xinming Li, xinming.li@ualberta.ca, University of Alberta
Yongsheng Ma, mays@sustech.edu.cn, Southern University of Science and Technology

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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. 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 [1]. Many people wear ill-fitting shoes every day due to the uniqueness of their foot shape, leading to foot fatigue, damage, or even disabilities [2]. 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.

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 [3]. 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 [4]. 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 [5] or in a discrete point cloud format [6]. 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 [7]. The above-mentioned shoe-last modeling method can produce relatively accurate models. However, its flexibility for design customization is limited. The customization process is tedious and time-consuming, and advanced shoe-last design knowledge is needed. In addition, after generating the model, quick editing and modifications are not possible, as parameters need to be adjusted manually, followed by the regeneration of surfaces. The operational complexity of modifying the model makes it challenging for ordinary manufacturers to implement. Moreover, from the designers' perspective, even if such a model modification process can be realized, it may still be difficult to design a shoe-last using an unfamiliar model.

This paper introduces a method for automatically constructing a parametric CAD model of a shoe-last structure based on features. 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.

<u>Main idea:</u>
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 Fig. 1. Initially, a 3D foot scanner is employed to capture foot data from the experimental subject (customer). 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.

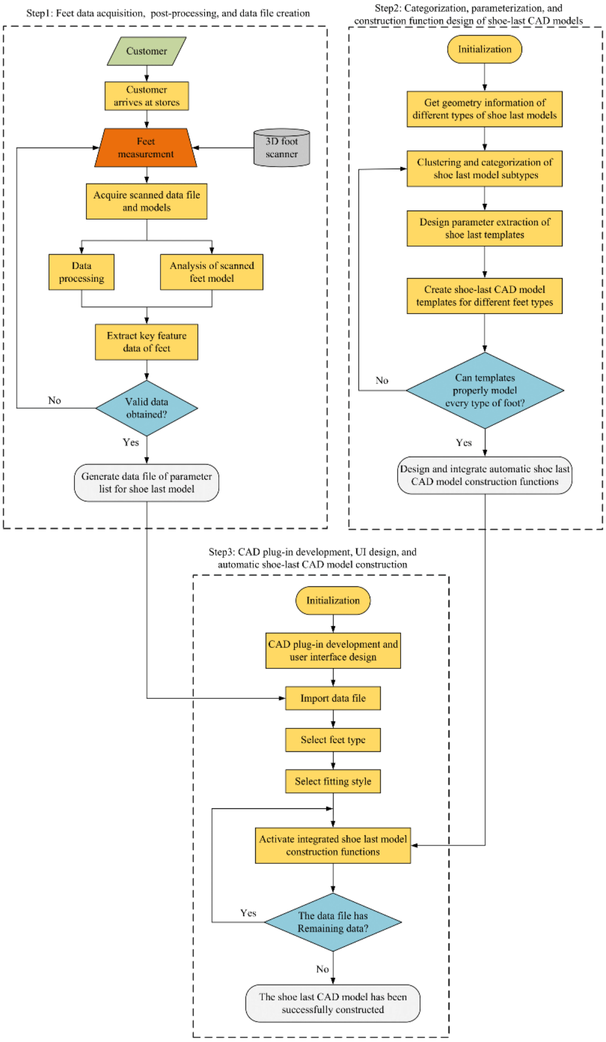


Fig. 1: Flow chart of the proposed method framework.

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 Fig.2). The updated data format builds upon conventional data representation, incorporating additional information to enhance design flexibility.

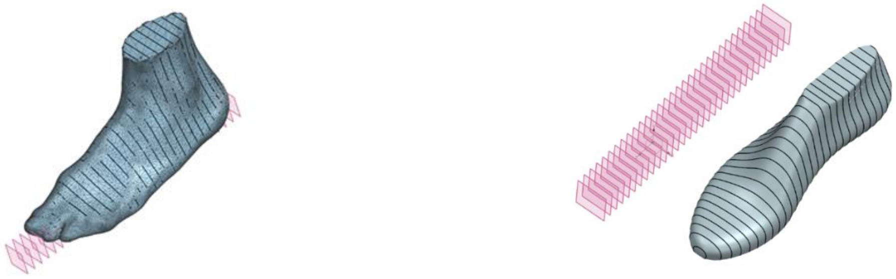
In traditional shoe-last production process, 3D scanning is used in creating shoe-last models. The process involves precise scanning and measurement, digital management and modification of lasts, and 3D printing. This approach allows for the production of footwear that is tailored to individual foot 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 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.

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

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 Fig.3 (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 Fig.3 (b)).



(a) (b)

Fig. 3: N sections are intersected with the model to obtain the section curve diagram: (a) N sectional lines intersecting with the human foot model, (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 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 10mm and 200 characteristic points on each cross-section are sufficient to obtain accurate shoe-last models based on different foot shapes. As shown in Fig.3, 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.

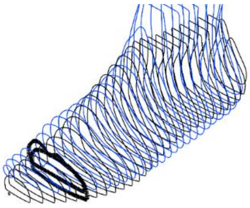


Fig. 3: Comparison of the characteristic points on the human foot cross-section (blue) and the cross-sectional characteristic points on the standard shoe-last model (black).

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 Fig.4). This process is repeated for each of the N cross-sections.

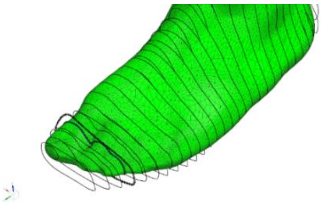


Fig. 4: Characteristic points on the adjusted shoe-last section.

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.

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 automatically modify the model. 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 has 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.

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 US9 size foot with a wide foot shape is used as the case study. After importing the data file, the standard shoe-last model of the same size (US9, 270mm) was selected from the library. It can be observed that the foot feature model is noticeably wider in the forefoot region compared to the standard shoe-last model (see Fig.5(a)). Starting from the far-left end of the X-axis of the foot 3D scan model, cross-sections were inserted at 10 mm intervals to obtain intersections with the 3D scan, here we inserted 26 cross-sections. For each intersection, 200 feature points were extracted. The same method was employed to obtain cross-sectional lines and feature points for the corresponding standard shoe-last model. Through our proposed algorithm, points extracted from the standard shoe last model that did not fall within the cross-sections of the scan model were adjusted automatically to generate a new shoe last cross-sectional curve. A new surface was formed through curve stitching (see Fig.5(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.

(a) (b)

Fig. 5: An automatically constructed customized shoe last model: (a) Comparison of US9 wider foot (green) and US9 standard shoe-last (concrete); (b) An automatically constructed customized shoe-last model with wider forefoot region.

Conclusions:

In this paper, an automatic CAD model construction method for shoe-last is proposed as the conceptual framework, developed in a CAD system, and validated through a case study. Utilizing a new data representation for diverse foot shapes and parameterizing different foot characteristics, the proposed method achieves an automatic CAD model construction of a customized shoe-last. The constructed models are feature-based parametric models with better compatibility, editability, and design flexibility.

Future work involves integrating a library with more types of foot shapes and deformities into the shoe-last construction function to automatically generate models with a wider range of shoe-last categories for further validation and application of the proposed method.

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References:

[1] Cheng, F.; Perng, D: A systematic approach for developing a foot size information system for shoe last design, 171-185. https://doi.org/10.1016/S0169-8141(98)00098-5
[2] Jiao, Y.; Džeroski, S.; Jurca, A.: Analysis of hallux valgus angles automatically extracted from 3D foot scans taken in North America, Europe, and Asia, Structural and Multidisciplinary Optimization, 66(8), 2023, 1164-1175. https://doi.org/10.1080/00140139.2022.2139415
[3] Luximon.; Ameersing.; Xiao, M.; Luximon,Yan.: Design and manufacture of shoe last, 2021. 215-242. https://doi.org/10.1016/B978-0-12-821606-4.00009-0
[4] Xiong, S.; Zhao, J.; Dong, M.: A computer-aided design system for foot-feature-based shoe last customization, 46(1-4), 11-19, Jan. 2010. https://doi.org/10.1016/S0895-6111(03)00032-6
[5] Rout, N.; Khandual, A.; Zhang, Y.: 3D Foot Scan to Custom Shoe Last, 110-114, Apr. 2010. https://doi.org/10.47893/IJCCT.2010.1030
[6] Wu, M.; Jiang, K.; Liu, B.: Customize shoe last made to order, 24(1), Feb. 2009. https://doi.org/10.1103/PhysRevB.93.115428
[7] Buades, J.; Gonzalez-Hidalgo, M.; Perales.F.; Oliver. A.; Ramis-Guarinos.S.; Blanch.V.: A new parallelizable deformation method: Automatic comparison between foot and last, 2012, pp. 363-369. https://doi.org/10.5220/0003860803630369