N91-23051

A SEMI-AUTOMATED PROCESS FOR THE PRODUCTION OF CUSTOM-MADE SHOES

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INTRODUCTION

A more efficient, cost-effective and timely way of designing and manufacturing custom footware is needed. Over one-half million Americans cannot comfortably wear off-the-self, mass-produced shoes. Their requirements for custom-made shoes result primarily from congenital defects or from having worn improperly fitted footware, but a substantial portion of these individuals have had partial amputations of the foot. However, custom-made shoes, particularly orthopedic shoes, are usually very expensive because their design and manufacture is now a highly skilled and labor intensive process; and their delivery times are often long, and getting longer, because the number of skilled shoemakers in this country is inadequate and declining rapidly.

A potential solution to this problem lies in the use of computer-aided design and manufacturing (CAD/CAM) techniques in the production of custom shoes. Although these techniques are being used in the design and manufacture of mass-produced shoes, they have only recently been applied to the production of custom shoes. In 1984, two workshops to "Establish Criteria for the Development of a Computer-Aided Design (CAD) System to be Used in the Construction and Custom Contouring of Orthopedic Footwear through Computer-Aided Manufacturing (CAM)" were sponsored by the National Institute for Handicapped Research (now National Institute for Disability and Rehabilitation Research). These workshops revealed a general consensus among the participants that the technology existed and the time was ripe for the development of a cost-effective, highly automated system which would use CAD/CAM techniques to design and manufacture custom shoes[1].

In 1985, the momentum generated by those workshops resulted in the initiation of a cooperative inter-agency project to develop such a system. This project, supported equally by the Veterans Administration (VA) and NASA, has been carried out under the technical direction and management of NASA with the support of Research Triangle Institute. NASA's involvement in this project has been motivated by an opportunity to apply NASA-developed technologies, specifically the computer programs NASCAD (NASA Computer-Aided Design), RIM (Relational Information Management) and the NASA version of APT (Automatically Programmed Tools), to the solution of this problem.

Using the workshop data and recommendations as a starting point, a prototype computer-based system has been developed by a team of programmers and engineers supported by grants to North Carolina State University (NCSU) and the University of Missouri-Columbia (UMC). This system is primarily a software entity which directs and controls a 3-D scanner, a lathe or milling machine, and a pattern-cutting machine to produce the shoe last and the components to be assembled into a shoe. The steps in this process are: 1) scan the surface of the foot to obtain a 3-D image; 2) thin the foot surface data and create a tiled wire model of the foot; 3) interactively modify the wire model of the foot to produce a model of the shoe last; 4) machine the last; 5) scan the surface of the last and verify that it correctly represents the last model; 6) design cutting patterns for shoe uppers; 7) cut uppers; 8) machine an inverse mold for the shoe innersole/sole combination; 9) mold the innersole/sole; and, 10) assemble the shoe. For all its capabilities, this system still requires the direction and assistance of skilled operators, and shoemakers to assemble the shoes. Currently the system is running on a SUN3/260 workstation with TAAC application accelerator. The software elements of the system are written in either FORTRAN or C and run under a UNIX operator system.

DETAILING THE PROCESS

Currently foot scans are being made with a commercially available 3D laser scanner, the Cyberware Model 4020. This scanner records approximately 250,000 points, which are registered in latitude, longitude and radial distance. These measurements are made with an accuracy of better than 1% and a resolution of 0.7mm. It only takes about 15 seconds per foot to acquire this data. The foot can be either in a "neutral", or partially or fully loaded position. Since the scanner can also obtain foot surface data from models made from plaster casts, this data can also be obtained on people who cannot come to the scanner location for the measurements. By January 1991, a new model scanner, designed by Cyberware specifically to acquire foot surface data, will be integrated into the system. The advantage of the new scanner is that it is more convenient to use and is also easily portable.

CREATING A REALISTIC MODEL OF THE FOOT

Thinning data

The high density data is needed only in those areas where the foot surface changes rapidly and thus needs to be represented in more detail, i.e. the heel and toes regions. In the other areas of the foot the changes in the surface can be effectively represented by only a few data points. A thinning routine has been developed which can relate the surface data density required to the rate of change of the surface. This routine is used to reduce the size of the data set to a minimum consistent with an accurate representation of the foot. This process minimizes the RAM storage requirements and speeds up the subsequent computations.

Foot models

The foot surface data can be represented by any of three different models,, i.e. a "point" model, a "wire" model, or a "tiled" or "shaded" model. The model selected to display the foot is a function of the process using the model. The point model is the least detailed and is thus the least realistic representation of the foot. It is used primarily for speed. When the foot is rotated from one view to another, the point model is used. The shaded model is the most realistic representation of the foot, but is the most time consuming to display. It is used when it is necessary to get a "feel" for the shape of the foot and the details of its surface. The wire model is intermediate in realism and speed.

Rotation, color and lighting

To help provide the user with a realistic foot model, options are provided which allow shaded model rotation, coloring, and illumination. There are two rotation options: continuous and interactive rotation. The latter allows the model to be rotated among six standard views; i.e., front, back, right side, left side, top and bottom. Continuous rotation can be used to set the foot spinning on a selected axis and at a selected rotation speed. This option can be used to simulate turning a plaster foot model by hand. Color options are available for both the shaded foot model (four colors) and the background (five colors). The illumination option allows the shaded model to appear as if illuminated from any direction selected by the operator.

INTERACTIVELY DESIGNING THE SHOE LAST MODEL

Once the foot requiring a custom shoe has been scanned, and the digitized data transferred to the computer, thinned, and presented to the operator as a foot model, the next step in the process is for the operator to interactively modify the foot model to produce a shoe last model. The shoe last modeling subsystem, called LASTMOD, provides a menu-driven user interface which allows the operator to perform the needed functional and aesthetic modifications without extensive training or familiarity with computers[2]. The operator can select from six different operations to achieve the modification(s) desired. These operations are "Add Volume", "Remove Volume", "Toe BuildUp", "Extend Toe", "Region BuildUp", and "Region Move". In addition to being able to view the modified model between operations, the operator can compare the current modified model with the original foot model at any point in the process. The operator can also rotate the model and/or magnify selected areas of the model.

Add Volume/Remove Volume

These operations are used to add or subtract a slab of material along a previously defined cut plane, with or without a reference plane. Material below the reference plane, usually the planar surface of the foot, remains unaffected. The "Remove Volume" operation is used primarily to narrow the ankle part of the last.

Toe BuildUp/Extend Toes

These operations are used to either add material to the toe end of the last or to extend (stretch) the toe region of the last. This provides a toe "box" at the end of the shoe, allowing freedom of movement for the toes.

Region BuildUp

This operation adds material to the last in areas where the patient has an ulcer, corn, bunion, or other sensitive area that requires relief of pressure. Selectable variables include location of the entire edge of the area, the maximum thickness of the buildup, and the location of the maximum. Marks made on the foot before scanning show up on the screen in a different color and can be used as reference points.

Region Move

This operation moves a section of the last, usually a toe, away from the main body of the last. The space between is then automatically filled.

Patient Data

To aid the operator in the interactive process, a patient database feature has been included in the program. Called the "Patient Information Database", it provides a mechanism for storing and accessing data equivalent to that gathered by the practitioner (podiatrist or pedorthist) through interviews and examinations of the patient. This data is primarily actual foot measurements, related biomechanical data, and the patient's medical and orthopedic history. This database has been implemented using R:BASE for DOS (version 2.1) and RIM 5 database management systems.

MACHINING THE LAST

Once the last model is complete, it is resampled with a user specified tolerance and then represented using the minimum number of Coons (parametric bicubic interpolatory) patches[3] to maintain accuracy requirements. The data set that represents the final model is then transferred to the Tool Path Generating and Machining Subsystem (LASTCUT) to generate cutter location data. LASTCUT generates the tool path data using one of two distinct methods: APTGESS[4] or SSURF[5]. The primary difference between these methods is that the APT-based programs generate general cutter line data which must in turn be converted by a post-processor[6] (UPOST) into appropriate machine-specific data, while SSURF creates tool path data directly from the shoe last model. Thus the APT-based method is slower and can have problems at interfaces between sculptured surfaces (37 patches maximum), but because the post-processor is "universal" it is applicable to any 3, 4, or 5 axis CNC milling machine tool. While SSURF is faster and can handle an almost unlimited number of Coons patches, it has no algorithms to check for tool gouging.

Before the shoe last is machined, NASCAD is used to view and, if necessary, plot the tool path. This is done to check for errors in programming or data processing. The milling of the shoe last is currently being performed on a 3-axis milling machine which has been modified by the addition of a rotary table.

VERIFYING THE SHOE LAST

After a shoe last is machined, it is scanned and a computer model is generated. A verification subsystem then compares the dimensions of the computer-generated last model with those of the machined last. This subsystem checks for machining errors and.decides whether the machined shoe last is within acceptable tolerances. The verification subsystem uses a simularity measure based on spine deviation, section size variation, section elongation variation, and section orientation variation. The spine is a line which passes through the centroids of a series of cross sections of the last model. The simularity measure is actually a weighted root-sum-of-squares of the differences.

DESIGNING AND CUTTING SHOE UPPERS

A computer program which can be used to design and direct the cutting of shoe uppers is commercially available from Microdynamics of Dallas, TX. We are currently trying to interface the output of LASTMOD with this software. This capability will also allow the introduction of styling considerations into the final product.

MACHINING THE MOLD AND CASTING THE INNERSOLE/SOLE

To produce a shoe sole with maximum fit and comfort, it was decided to cast an innersole/sole combination in a mold which reflects the plantar or bottom surface of the foot. An output file generated by LASTMOD is used to machine the mold from wood or plaster. The bottom surface of the mold is an exact reproduction of the inverted plantar surface of the foot. The orientation of that surface is variable according to the need for heel pitch (how much higher the heel will be than the toes), and the balance line (the angle the leg deviates from the vertical). The mold can also be made deeper to accommodate a shorter leg by a thicker sole. The sole mold is currently being machined on a 4-axis CNC milling machine.

There exists a wide range of materials from which the innersole/sole combination can be cast. Currently a quick-set latex material is being used for demonstration purposes. It was selected primarily on the basis of convenience, and thus other materials may be more applicable to shoe construction, wear, comfort, etc. Also a liner may be needed to separate the foot from the sole and give more comfort and better wear characteristics. The liner could easily be bonded to the inner surface of the sole during the shoe assembly operation.

ASSEMBLING THE SHOE

The shoe assembly process still continues to be a manual process, but there is hope that it can be at least partially automated. This effort was outside the scope of this program, but may be addressed in any subsequent phase. At this point in the development effort conventional assembly is still being used.

STATUS/FUTURE PLANS

All work towards development of a prototype system will be complete by the end of calendar year 1990. Currently a demonstration phase is underway. Two pairs of orthopedic shoes are being made using the above process. The system software and hardware will soon be turned over to the Veterans Administration for clinical testing. Once this testing is complete, a second development phase will begin which will optimize the system and make it operational. This work will probably be supported solely by the VA.

ACKNOWLEDGEMENTS

This work has truly been a team effort. Each grantee has made a significant contribution to the total effort, as has each of their students. The contributions of each team member is hereby acknowledged and their areas of responsibility delineated:

- Dr. David McAllister, Professor of Computer science, Ncsu (LASTMOD, uppers design/cutting interface, project coordinator) ; J. Pietenpol, L. Harrison, S-H. Yang, D. Carver, P. Hebbar, R. Devarjan, M. Patel.

- Dr. Ren Luo, Professor of Electrical and Computer Engineering, NCSU (Last Shape Verifier, scanner interface); Y. Kim.

- Dr. Han Bao, Associate Professor of Industrial Engineering, umc (sole/innersole design and mold machining processes) ; S. Gharagozloo, J. Ainumtip, R. Aiyar, N. Lin.

- Dr. William Rasdorf, Associate Professor of Civil Engineering and Computer Science, NCSU (patient data base, NASCAD-RIM interfaces); S. Lakmazaheri, L. Boose, 0. Abudayyeh.

- Dr. Ezat Sanii, Assistant Professor of Industrial Engineering, NCSU (APT IV modifications and NASCAD interfaces, SSURF); H. Chou, L. Colbert, K. Srinivasan, C. Zhow.

- Mr. Robert Wallace, Industry Specialist, RTI (management support, project coordination, consultants).

Also, I would like to acknowledge the contributions of Dr. Margaret Giannini, Mr. Don Vargo, and Mr. Wijitha Ellepola, VA Central Office, Washington, DC; and Mr. Ray Gilbert, NASA Headquarters, Washington, DC.

REFERENCES CITED

1. Rouse, D.J.: A Proposed Design for an Orthopedic Footwear CAD/CAM Delivery System. DOE Contract #300-83-0236, 1984.

2. Pietenpol, J.L.: Computer Graphics System for the Interactive Design of Shoe Lasts. M.S. Thesis, North Carolina State University, 1989.

3. Coons, S.A.: Surfaces for Computer Aided Design of Space Forms. MAC-TR-41 Project MAC, M.I.T., 1967.

4. Srinivasan, H.: APT Program Generator for the Computer Aided Manufacture of Custom Orthopedic Footwear. M.S. Thesis, North Carolina State University, 1989.

5. Colbert, L.: SSURF - A Tool Path Planning System for Machining Three-Dimensional Sculptured Surfaces. M.S. Thesis, North Carolina State University, 1989.

6. Chou, H.L.: APT Universal Postprocessor for Multi-Axis CNC Milling Machine Tools. M.S. Thesis, North Carolina State University, 1989.