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INNOVATIVE DESIGN AUTOMATION TECHNOLOGIES FOR CORRECTIVE SHOES DEVELOPMENT

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1. Introduction

The paradigm of Mass Customisation (MC) is today fundamental for the European fashion industry. The basic theoretical concepts of MC and its applicative methodologies have been well defined in these last years, on the other hand the lack of suitable supporting technologies has been a strong obstacle to a real application, especially for SMEs [Jiao et al. 2003].

In the corrective shoes field the mass customisation principles have to be necessarily adopted to satisfy the heterogeneous and specific customer requirements. Furthermore the compromise between aesthetic and functionality, considered as malformation/imperfection correction, is stressed. Designers sometimes have had a tendency to create products that are not well suited to their buyers. In fact, the product must be adapted to the wearer, and the product's characteristics must change in accordance with the buyer's preferences and their individual shape, size and defect. The final shoes appearance must be similar to a standard fashion product to avoid a sort of negative identification.

Footwear industry is still labour intensive and companies need solution to reduce costs and remain competitive in the global market, in particular, the specialized companies that produce corrective shoes due to the small batches realised. The production is often completed with customized medical shoes prescribed for people with feet malformations and they are produced in unique pairs. Manual operations and the personal experience of artisans are still key factors to manufacture high quality products, but the lack of such human resources will be an obstacle to locally maintain this kind of production.

For these reasons small enterprises need to convert their plants to mass production paradigm to compete in the market and to sustain a growth.

CAD modelling, biometric studies, flexible manufacturing systems and web technologies are enabling the costs involved in product personalisation to be reduced. This means that providing personalised products to the mass market is becoming increasingly economically viable.

The research effort is particularly focused on new 3D design tools and reverse engineering technologies applied to the European fashion industry, as the E-Tailor (www.atc.gr/e-tailor) and eT-Cluster (www.atc.gr/eT-Cluster) projects have demonstrated. But, as the Textile/Clothing Working Group wrote three years ago [AA.VV. 2002], "the results of these projects constitute a sound basis for further research in areas such as 3D whole-body scanners and related automatic measurement algorithms, body shape analysis, …". Thus, even if the recent results of research activities are allowing to the first practical applications, especially in the footwear field [Boer 2003], several open issues for an effective MC exploitation have to be still approached. A rethinking of design and manufacturing systems leading to a better interoperability of tools related to different product development phases (from conceptual design to material recycling), a better integration between

design tools and web-based technologies, a better "usability" of systems by final users, generally non-technologically skilled, and, finally, an improvement of product development supporting tools technical performances, are some basic long-term objectives of research.
In this context, this work presents some approaches and low-cost solutions related to foot measurement and CAD data elaboration for facilitating the diffusion of "made-to-measure" products. The systems are under development for the footwear industry and, in particular, the basic ideas and principles can be successfully applied in the corrective shoes development field. An integrated process made of hardware devices and customized software is explored and described aiming to increase production efficiency and reduce costs.

2. State of art

In terms of shoes design and manufacturing, many dedicated Information Technology (IT) systems have been deployed in the last decades to support the product development processes but, currently, none of them provide a satisfactory answer to small manufacturers. On the one hand, general purpose CAD systems offer good integration and different file format exchange possibilities. They are reliable, precise and could offer a valid support in shoe design. The main problem is related to the lack of dedicated packages designed to speed up specific 3D modelling operations. Some attempts in this direction, on the other hand, have been made by some software developers, such as Lectra, Newlast and Shoemaster. They are mainly conceived to realise 3D virtual models of shoes useful for marketing purposes and to manage specific manufacturing operations (upper cut, shoe sole moulding, etc.). However, systems lack of robust 3D geometry kernel, which causes shortness of accuracy. Customers complain absence of tools to support the implementation of their specific requirements and to integrate the different software solutions present in the manufacturing cycle. In fact different proprietary file formats, linked to the specific CAD solution, have arisen during the last years, in order to maintain the own market share. This has caused high costs and low integration and consequentially lost of efficiency.
The first step in a virtual development of some essential parts of the shoes like the sole and the last is related to scanning technologies. Besides, personalised shoes require feet digitalization in order to cope with specific parameters and geometries. Traditionally, the 3D objects digitising has been carried out through mechanical feelers, often manually operated. Anyway, those devices present the inherent problems associated to the mechanical system as clearances, faulty functioning, inertias, etc…Up to now, mechanical digitisers have a precision around 0,1 mm, allowing the measure of 90 points by section, and with a minimum passage between sections of 1mm that in some cases of sophisticated objects represents a poor resolution. Furthermore, the process can be intrusive due to the mechanical pressure exerted on the object to be digitised. It can generate deformations on measuring object and it is unusable for direct foot digitalization.
On the other hand there are different sophisticated 3D laser- and fringe projection based scanners on the market which are able to scan numbers of physical objects and obviously shapes like lasts or feet (www.konicaminolta-3d.com, www.steinbichler.com, www.gom.com). Mass-customization and best-fit selection using these scanners have nevertheless not been successful up to now for a major reason: the required investments are just too high for a small shoe manufacturer.
The current research is mainly focused on simplify the 3D optical scanning devices for footwear industry in both standard and corrective field [Redaelli et Al. 2005]. Some examples of dedicated systems are appearing on the market focusing on affordable and ready to use technologies.
The Lightbeam 3D foot scanner (www.corpus-e.com) for instance is built to reduce the costs in using such a 3D foot scanner for retail shops. Just a small platform which is equipped with one digital video camera is needed. [Rutschmann 2005]. The customer has to step with a low-cost elastic garment on his feet, and the digitalization takes approximately 25 seconds per foot. The captured information is sent in the background to a server to process the 3D models and measurements of the individual foot.
The Canfit-Plus Retail 3D Foot Scanner (www.vorum.com) on the contrary, is a optoelectronic imaging device designed specifically to work with the Canfit-Plus Retail System. Using this system, a retailer again can measure a customer's foot, select the best fitting last for the styles selected by the customer, and make arrangements for the manufacture of the appropriate shoes. Luximon [Luximon

2005] proposes a method which enables footwear fit quantification so that fit-related comfort may be predicted. Using Canfit-Plus Foot Scan the method has been validated to choose the "best-fitting" last from a group of available lasts.
Finally, Pedus Foot Scanner (www.vitus.com) has been designed specially for the shoe manufacturers, to measure feet three-dimensionally within only a few seconds. The individual customer may choose the most favorable and comfortable pair of standard shoes or he can order a specially made-to-measure shoe. Using digitized models produced with this scanner Novotni et Al. [Novotni 2001] have proposed a 3D object comparison method to incorporate locality by assigning local weighting of the geometric distance function to the surface, in order to be able to differentiate between relevant and less relevant areas of the investigated feet.
Anyway, none of these systems joins sufficient accuracy and rapidity with low cost and simplicity required in actual companies' process. Mainly, solutions present on the market target shops and hardly integrate in a design and production process. Our proposal delineates a solution which tries to give an answer to the growing interest in mass customization implementation in footwear industry.

3. Corrective shoes development process

3.1 Corrective shoes

Every corrective shoe has its own specific characteristic in dependence of the particular foot morphology and defect. They are produced in unique pairs with differences between the left and the right one.
Traditionally, feet dimensions are measured along specific curves by trained doctors or technicians who provide the manufacturers with forms filled with all necessary geometrical and dimensional specifications. For the most complex cases a plaster cast of the feet is realised in order to capture the shape better than discrete local measurements.
In the production process almost all the components must be shaped on the basis of the specific foot: the sole, the upper part and the last, a block shaped like a foot made in wood, plaster or plastic necessary to assembly the shoe. Only few accessories can be borrowed from mass production like strings, etc…
Lasts are created starting from a set of standard shapes, choosing the one that better approximates the foot. Then manual work is done on it by thickening with cork sheets where necessary and removing material with sandpaper. This process is repeated until the last meets the required measurements.
Upper pieces geometries are extracted by overlapping the last with gummed paper stripes, which finally are cut, removed and flattened on plane. Soles are obtained from preformed ones cut to the desired shape. Then shoe assembly follows the traditional process that is sewing the leather and joining to the sole. The whole process is basically handmade.

3.2 Proposed design process

The studied system aims to support the design of a customised last in a short time automating the main phases of the process. The main efforts have been dedicated to experiment technical solutions where the relation cost/benefit is optimal. Software/hardware integration has been pursued in order to make this solution affordable, complete and efficient in terms of design benefit. The system is based on an optical 3D acquisition tool (laser telemetry technology), avoiding the problems of the mechanical feeler. The high-speed and versatile 3D laser scanning system combines mechanical and control technology with an applied sensors system based on telemetric principles of laser technology, for the measure of feet or last. The integration of measurement data with dedicated CAD software tools allows generating the virtual last considering the necessary corrections of foot defects in a semi-automatic way.
As shown in fig. 1, firstly a scan of the foot is necessary. The scan result is composed by a large number of points characterized by their spatial coordinates. Software has been developed to be used in combination with the scanning device, in order to obtain all typical foot measurements: foot length, foot breadth, girth circumference, etc… Key points are selected on the points cloud data and then

proper algorithms calculate parameters values and draw curves on the points. These values are used to fill in the electronic patient form with his personal and morphological data.

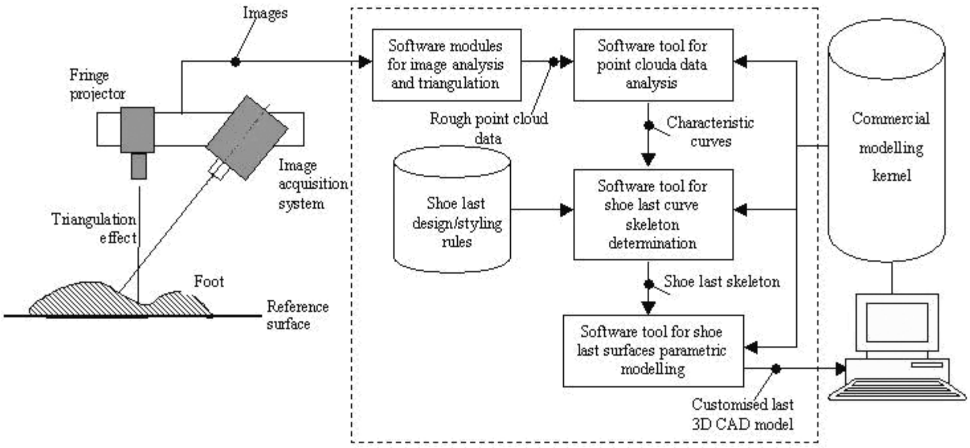

Figure 1. Proposed last design process flowchart

The digitizing system can also be used to scan physical lasts and obtain virtual models. Doing so for different standard lasts it is possible to build a database including the starting shapes, which will be employed afterwards. A complete database should include different sizes, and alternatives for man and woman, high and short shapes, different heel heights, etc…

A suitable last has to be selected from the database in order to meet as good as possible the patient desired shoe and his foot parameters. Since the virtual last is obtained from scanning process it has to be converted from points cloud data to triangulated representation (STL), operation that can be performed with the mentioned software under development.

The main critical part of the process is the virtual last modifications needed to correct the patient defects consistently with the fashion dictates. As result of the process a set of NURBS surfaces is obtained in order to produce the lasts by milling on one side and to unroll them in pieces which can be cut from leather.

To deal properly with all these geometry elements (mesh, curves, NURBS surfaces, …) the Software Development Kit of a low-cost commercial CAD software (Rhinoceros v.3.0) has been employed.

A dedicated software application, called *Last Designer*, has been developed using the programming language MS Visual Basic.NET. A set of dedicated modelling functionalities has been implemented to cope with foot and lasts points cloud data, lasts geometry editing, modifications and exporting to milling devices and leather cutting.

4. Foot and last 3D digitalisation system

4.1 3D laser digitizing system

The laser 3D digitiser developed is an automatic digitising system for 3D objects in 3 dimensions by means of laser telemetry and a multiaxial movement system. This digitiser is composed by a set of devices and electromechanical and electro optical elements synchronised, through appropriate software, in order to carry out different readings from the surface of the 3D object to be digitised. This way it is possible to obtain a virtual image of the object that is introduced in a CAD environment through the adequate channel.

The part to be digitised is placed on a spin axis, in such a way that we obtain successive sections of it synchronising complete turns of the object with linear displacements of the telemetric sensor. The technical specifications of the digitiser are to be considered in relation of the particular application. The resolution is about 0.1mm and the distance between sections varies with minimum increments of

0.5mm. These are poor characteristics for a mechanical application but enough for a foot scanning device witch has to combine them with high digitising speed and easy use.
The system is composed of a mechanical part, another one of electronic control based on a multicard design, and a third part of management of capture signals in a high level graphic environment.
The mechanical system is based on a metal framework that supports the set of active and passive mechanical elements. Furthermore it is used as support of the low level electronic system (figure 2).

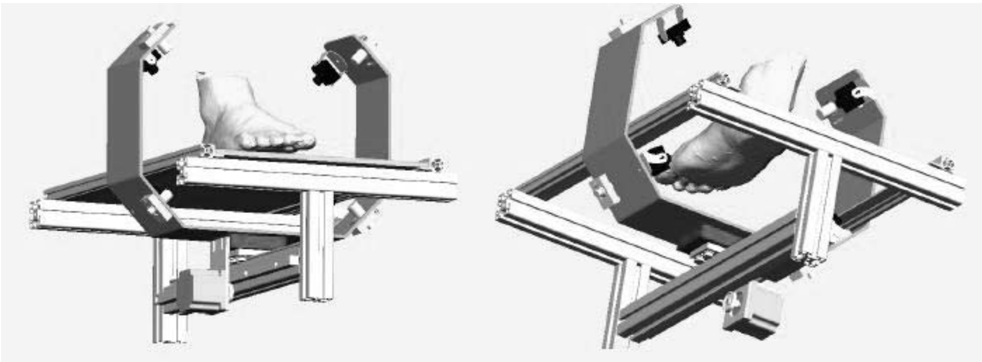

Figure 2. Foot and last 3D digitalization system scheme

The movement system is composed by a set of two linear displacement systems, one for vertical displacements and the other for horizontal ones, and by a rotating platform in which are placed objects to be digitised. Stepper motors, adequately sized in order to execute all the movements with the same precision and in the time conditions required, carry out the movements.
This system carry out a low level control of all the signals in order to synchronize in real time the following aspects: displacements of the different axis by means of stepped motors, settings of the telemetric system, computer system communications.
The architecture defined is based on a system of several microcontrollers, and therefore the different functions can be deployed in real time.
A critical part of the system is the telemetric system based on a laser triangulation measuring systems with high-resolution linear CCD sensors, in a double configuration. This technique has been developed in his different aspects for the manufacturing of this kind of sensors, not only at mechanical level but also at electronic level and in assembler code programming. The control and treatment of low-level signals of this telemeter is carried out by means of a specific circuitry designed for that aim. This system combines a high-speed treatment logic and a microcontroller system from a high speed version of the family 8031, so it is possible to synchronize and to control the movements and readings in real time.
A fundamental part of this system is the alignment set of the telemetric sensors, in fact the required precision can only be matched if the alignment between the different elements has a high precision.

4.2 Control software

The control software implemented for the optical digitiser allows carrying out several actions such as the digitiser configuration and calibration, obtaining specific points sections from the object to be digitised, obtaining preliminary curves and surfaces from those points, flattening, edition and visual display of those curves and surfaces. The application has been implemented in C++, in a Windows-based environment, and allows the user to work in an friendly and easy to use interface.
From the points sections obtained, the system creates preliminary rough interpolation curves conforming the final sections in such a way that they can be more easily edited offering a higher smoothness degree. Filtering algorithms are based in Gauss filters that allow to define a higher or lower flattening degree due to the fact that some curves can require a higher filtering.

A specific file format has been implemented allowing storing the original and filtered curves, and also the surfaces obtained in order to retrieve them later. Furthermore, the application allows to export the curves and surfaces generated to the geometric formats more used such as IGES, DXF and VDA.

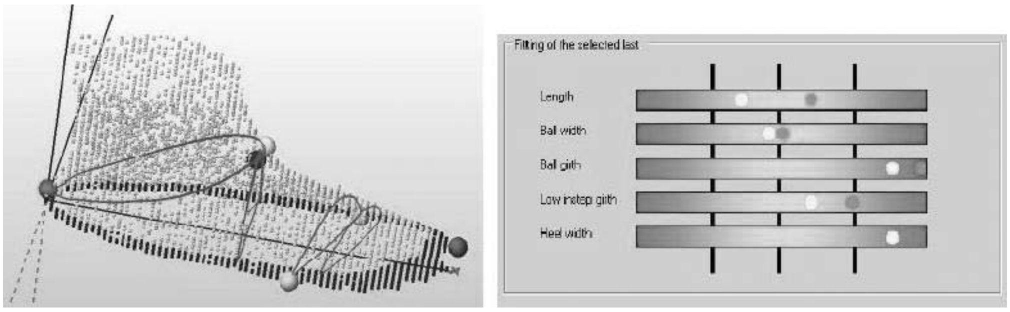

Figure 3. Foot parameters extraction and fitting with database lasts

The application has a work editor with the 3 basic views in 2D as well as a 3D view for the visualization, treatment and edition of curves. The system is equipped with a layers manager allowing to at least have one layer with the digitised curves at first and other one with the flattened curves. These layers can be visualised, blocked, colour modified, etc… Finally, a realistic rendering based on the graphic library 3DR offers to the user a view of the digitised object very similar to the real one.

5. ***Last Designer*** software

Once a standard last has been chosen as starting point, a digital model is created through the 3D scanning tool. The model has to be imported in Rhinoceros and it is possible to work on it through a number of customized modelling functionalities, which have been gathered together in *LastDesigner* software package.
Figure 4 shows the sequence of operations to carry out in order to obtain a customized last.

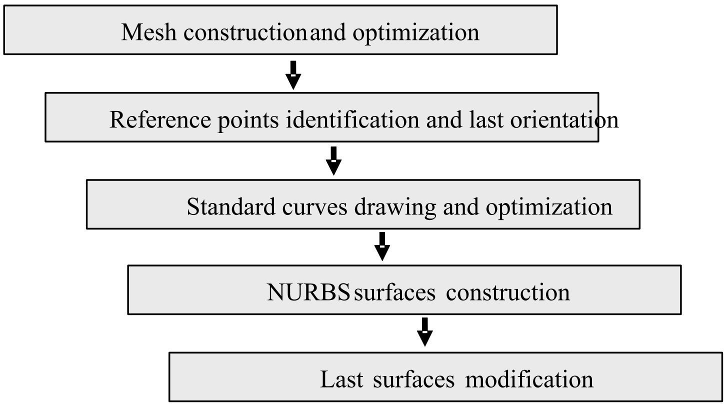

Figure 4. Last Designer functionalities and flowchart

Firstly, a triangulated mesh has to be built from points cloud data. This operation may lead to some errors in the STL model and all the corrections must be performed: holes filling, non manifold faces deleting, noise reduction, mesh decimation, isolated triangles deleting, etc… All these operations have been implemented through automated commands, easy to use also for non skilled operators.
For the sake of simplicity a standard last reference coordinate system has been fixed. The operator identifies some standard points on the last scan in order to fix styling and space references. The last is then positioned in its coordinate system.

Through reference points standard curves can be drawn. These curves include base edge curve and ankle curve and are necessary for the subsequent phase of surface reconstruction (fig.5). A semi-automated approach has been followed. The software provides curves laying on the mesh obtained through curvature analysis. Then the operator can modify or complete the curves especially where expertise is needed like the internal bottom part of the foot.

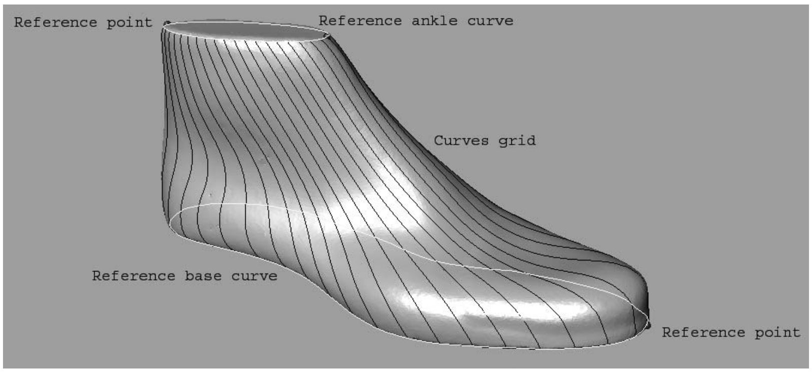

Figure 5. Reference points and curves for automated NURBS surface reconstruction

A curve network is generated as mesh sections and conveniently trimmed and smoothed. This operation is performed by a proper algorithm which uses reference points and curves to orient section planes. Curve network is then used to build NURBS surfaces as loft surfaces which is not trimmed and can be easily unrolled.
In this way, a sort of automated reverse engineering process has been obtained. This approach is particularly convenient for lasts. In fact, surface reconstruction has to be repeated many times, rapidly and automation makes it easy also for operators with poor reverse engineering knowledge.

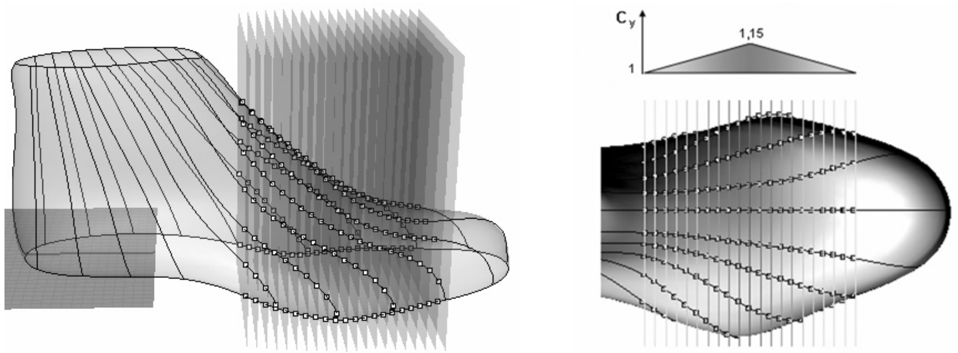

Figure 6. Example of last surface modification

Once a NURBS surface has been obtained, it has to be modified in order to meet patient specific morphological parameters. A number of standard modifications have been characterized from manual operators' expertise. Typically, these modifications refer to heel height variation, length or width increment, profile curves redrawing. In figure 6 an example of this modification has been provided. The objective is the rise of the last width. To preserve the styling and aesthetic shape, the amount of surfaces distortion has to vary from a maximum corresponding to a target section decreasing with the distance until it becomes zero. It has been obtained moving curves and surfaces control points on parallel planes calculating suitable correction factors.
Analogous approach has been followed for other modifications. The operator uses these functions in a proper sequence in order to achieve the required last shape which can considerably vary from the starting one.

Eventually, NURBS surfaces can exported in IGES format to milling machines to obtain a physical last or to other software packages for leather pieces preparing.

6. Conclusions and future developments

The outlined approach delineates a proposal to overcome low efficiency problems in lasts building especially in corrective shoes field. Low cost reverse engineering technologies and customized CAD software can substitute labour intensive operations and support small and medium enterprises to convert their factories to mass production paradigm and compete in the global market.

Corrective shoes production involves many phases based on manual operations. Using innovative technologies makes nowadays affordable to approach also other phases like sole design, upper cutting and shoes assembly in automated manner also for small batch production or unique pairs.

Future development of this work is related with full integration of customized software systems with production facilities in order to increase efficiency in each level of design and manufacturing process.

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