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A CASE STUDY ON CONCEPT DESIGN AND CAD MODELLING IN THE FOOTWEAR INDUSTRY

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1. Introduction

This case study is based on the experience of a collaborative project between the Faculty of CEMS at UWE and a European shoe manufacturer. The company has been producing footwear in Europe for more than a hundred years and whilst the methods used to engineer and manufacture soles and uppers have changed radically in recent decades, the methods used to style and design them remain very traditional. This approach posed no particular problems when shoe design, engineering and manufacture were co-located on the same site. Although the interface between design and engineering was inefficient from a product development perspective and this generally led to a prolonged time to market new shoe styles.

The European footwear market is very competitive in terms of the cost, quality and styling of shoes. These competitive pressures forced the company to consider the production of footwear in countries with low-cost economies. Design, prototyping, testing and evaluation were to remain in Europe, with leather uppers being manufactured in South America and moulded soles produced in the Far East. The need to communicate design concepts and product models thus became acute. Computer based geometric models of soles and lasts provided an obvious solution, but Shoe Stylists resisted the introduction of CAD tools for the early stages of concept design, preferring traditional media such as sketches on paper and hand-made models. The fundamental engineering problem was to convert these traditional representations into valid CAD models which could be used to support engineering activities in Europe and manufacturing processes in remote locations.

This paper is concerned with the tools and techniques used to develop valid CAD models from physical design prototype models of soles and lasts. Consideration is given to the collection of three-dimensional data and the use of this to support geometric modelling. The definition and representation of some key manufacturing features is discussed, and the use of CAD models to facilitate product development and manufacture in remote locations is presented. The effect of using geometric models to support design and product development and the lead time to market new shoe styles is also evaluated.

2. Concept design

Concept design is the first step in the process of creating a new product. Early stages in this process generally involve the divergent development of many alternatives, focusing on innovation, structure and function. Information gathering and brainstorming are typical activities at this stage, and there is considerable emphasis on the Designer's creative skills [Otto 2001]. With very few exceptions, notably aero and ship design, initial concept design is more the domain of the Stylist than the

Engineer. In the footwear industry, Fashion Designers are responsible for initial concepts, with Engineers playing a secondary role.
Concept Designers often prefer to work with traditional design tools, rather than computer-based ones. They perceive that traditional methods are less restrictive of the creative design process, and that sketches and physical models complement development and design evaluation activities. One of the major tools in concept design is the prototype model and one consequence of this is that Engineers are faced with the challenge of converting prototype concept models into CAD models at the appropriate stage in the product development/manufacturing cycle.

2.1 Design Prototypes

The footwear industry provides classic examples of Stylist using traditional tools for concept design and Engineers requiring valid geometric models for product development. The shape of shoes is developed from the inside shape defined by a carved wooden last and the sole is developed from a hand sculpted wax master pattern. Because of the artistic requirement, Designers produce sketches and drawings on paper and then Craftsmen create wood or wax models from these. Many major drawbacks lie in this method. Firstly, each kind of shoe requires a unique last and wax model. If these are lost or damaged, the shoe model can not be re-produced. Secondly, the physical archive is very large; it obviously requires a huge space to store the last and wax model for every shoe style and size. Thirdly, design revisions are costly and difficult to model and it is very difficult to communicate design intent to remote locations when physical models are used to define the product.

3. Virtual models from physical models

The process of developing virtual models from physical models is generally known as reverse engineering. This process can be summarised as follows: a physical model, usually of wax, wood or clay is made. This is then digitised, resulting in a mass of data points known as point-cloud data. A typical point-cloud data set would consist of several million position vectors. Point-cloud data gives a very low-level CAD representation of a digitised object. Hence, it is generally necessary to refine this data to develop high-level CAD models with a greater degree of utility. This process starts with tolerancing, triangulation and segmentation, and concludes with the application B-Spline or NURBS equations to fit surfaces and then skin the cloud of data points. This exercise leads to the definition of the faces, edges and vertices required for the creation of high-level three-dimensional CAD models.

3.1 Point-cloud data and triangulated surfaces

There are many devices on the market for the digitisation of three-dimensional parts. These range from vision systems, such as the ATOS system from GOM [Gom 2005], with the capacity to rapidly digitise areas up to a few square meters, to laser systems, such as DIGILAST 3D from Lectra [Lectra 2005] and contact scanning machines, such as the CYCLONE from Renishaw [Renishaw 2005], with capacities limited to a few square centimeters. The system selected for the digitisation of shoe models was the Renishaw CYCLONE scanning machine. This employs contact scanning using an analogue scanning probe. With this system, a ball-nosed probe tracks along the surface of the object and points are collected at the rate of 400 per minute. The positions of the points are stored in terms of x, y and z co-ordinates. The accuracy of the resulting points can be up to 10 microns and the system is almost noise free. Contact scanning with this system was found to be particularly appropriate for collection of surface texture information. Rough surface textures, such as those found on the soles of shoes, are difficult to capture using both vision and laser triangulation methods due the natural tendency of such surfaces to scatter light. It was found that contact scanning with small diameter probes (0.5mm to 1.0mm) provided an effective method for the collection of these textures.
The result of this data capture is a set of point-cloud data (figure 1). This stage is the starting point for the CAD modelling process and any inaccuracy of the points will be trailed during the whole process. Several problems might occur during the data capture stage, for example the machine possesses a 3-axis movement this means that inaccessible areas can be found in many components, for example re-entrant features. The way to overcome this problem is to take several scans in different directions and then to combine the multiple sets of point-cloud data in order to re-create the whole model.

The creation of high-level CAD models is a long and expensive process, requiring considerable user interaction. Consequently, it is essential to establish the need for this kind of model at the outset. A simple triangulated model, which is much easier to create, is adequate for many applications. For example, triangulated models facilitate the definition of CNC cutter paths and the generation of STL files for rapid prototyping. Basic transformations are also facilitated at this stage. The triangulated model can be scaled, female models can be created and other global alterations are available. Such models can be generated automatically from point-cloud data and the use of these models also avoids the need for subsequent stages in the creation of, more expensive, higher-level CAD models. A typical triangulated model of a shoe last is shown in figure 2.

Figure 1. Point-Cloud Data

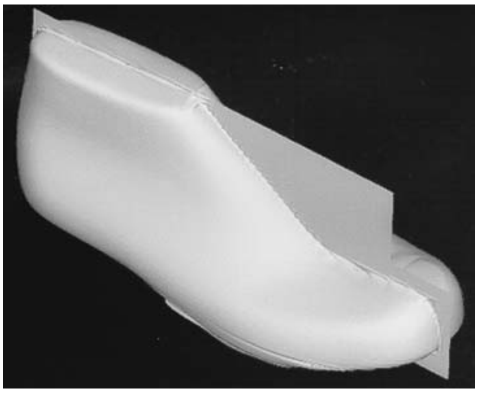


Figure 2. Triangulated Model

However, if there is a need for higher-level models, for example to create new features, utilise all the tools available within CAD design packages and facilitate localised modifications to the model, then it will be necessary to complete the processes of segmentation and surface fitting.

Initial stages in the implementation of the reverse engineering solution involved assessing the actual requirements of the last and sole models. The sole models are generally far more complex than those for the last, they often include complex surface textures and patterns to improve the market appeal of shoes. Models of soles are used to provide visual representations for design evaluation and for the generation of CNC cutter paths for the production of moulds and tools. Lasts are used to develop cutting patters for the leather uppers of shoes and to define the shape and fit of the inside of the sole. A fundamental feature on the last is the nominal edge delineating the sole and upper part of the shoe. Within the shoe industry, this is known as the 'feather edge'. This has fundamental implications for the style and fit of the shoe, and is a requirement for the manufacture of both soles and uppers. Localised modifications to the last model must be accommodated in order to facilitate minor revisions to the feather edge to refine style and fit. These observations led to the conclusion that triangulated surfaces were adequate for sole models, but last models would require fully developed surface patches with boundaries corresponding to the feather edge.

3.2 Segmentation

Segmentation is the process of subdividing point-cloud data sets and defining logical boundaries for subsequent surface patching operations. The segmented set of point-cloud data for the toe of a shoe last is shown in figure 3.

Segmentation is a crucial process affecting the general topology of modelled objects and the subsequent utilisation of these models for design evaluation and the generation of manufacturing data. The process of automatically segmenting point-cloud data along arbitrary boundaries has been investigated by many researchers; Ma and Manjunath [2000] proposed a technique for boundary edge detection and segmentation for surface reconstruction, Ip and Chan [1997] discussed the optimal segmentation of data for the development of geometric representations of radiotherapy masks. Arbitrary segmentation is useful in applications where the isolation of individual functional features on geometric models is not required, but it is often necessary to segment models of engineering components along functional boundaries. For example, parting lines on moulding tools and mating faces on assembled components are logical, functional, boundaries. At this point in time, techniques for the automatic detection of fictional features on point-cloud data are not well developed. Consequently the use of functional features for automatic boundary definition and model segmentation are not generally available. So this stage of the reverse engineering process usually involves considerable user interaction.

Hence, the segmentation process is a crucial step in the reverse engineering cycle. It is also the most approximate and is left to the discretion of the user because changes in surface characteristics are often not clearly defined on the point-cloud data.

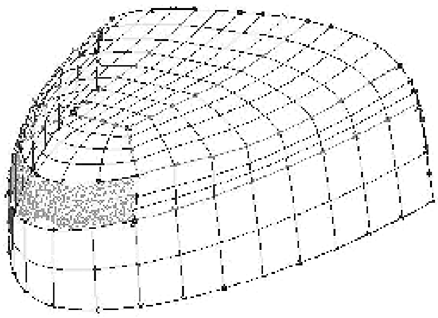


Figure 3. Segmented Point-Cloud Data

Finding an automatic segmentation procedure for free form components is a considerable challenge, particularly when functional boundaries are needed. The best segmentation methods would have no user interaction, would be very accurate and would take into account the functional and engineering requirements. Unfortunately such systems do not exist at the time of writing this paper.

In the context of shoe design and manufacture, a critical, functional, feature on the last model is the curve defining the boundary between the upper and sole of the shoe, that is the feather edge. This is of fundamental importance because of the different techniques used to manufacture moulded rubber soles and stitched leather uppers.

One of the main aims of this collaborative project was to develop techniques using sharp edges as construction lines to generate geometric representations of feather edges on shoe lasts. An important issue was then to find a way to extract the functional boundaries corresponding to these edges on point-cloud-data sets and to incorporate these into the segmentation process for the subsequent development of surface models. Section 4 explains how the proposed process achieves this.

3.3 Surface fitting

The simplest way to develop a three-dimensional model would be to fit a single surface to a complete set of point-cloud-data with one equation, but this is not generally possible because the complexity of the parts would lead to extremely complex surfacing algorithms. Hence it is normally necessary to divide the point data into a series of rectangular regions and to fit individual surface patches to these. The patches are then assembled, with appropriate boundary continuity conditions, to form a complete surface representation. The definition and creation of boundaries for these patches is known as segmentation (section 3.2).

The technique developed in this paper will use B-Spline patches to fit surfaces through digitised points. B-Splines have the benefits of flexibility and localised control properties and most commercial geometric modelling software includes B-Spline facilities. The properties of B-Splines are well documented and many researchers have studied the mathematical aspects of surface fitting with these. These patches are joined together with C^0, C^1 or C^2 continuity to facilitate appropriate curvature continuity conditions along the surface. There are several commercially available software packages with the capability of converting point-cloud data into three-dimensional surfaces. For example, 'CopyCAD' [Delcam 2005], 'TraceSurf ' [Renishaw 2005] and 'Romans RCS 3D' [Lectra 2005] all have the capability to trim, tolerance and segment point-cloud data and construct patched surfaces. A geometric model of a shoe last represented by 18 surface patches, developed using TraceSurf, is shown in figure 4.

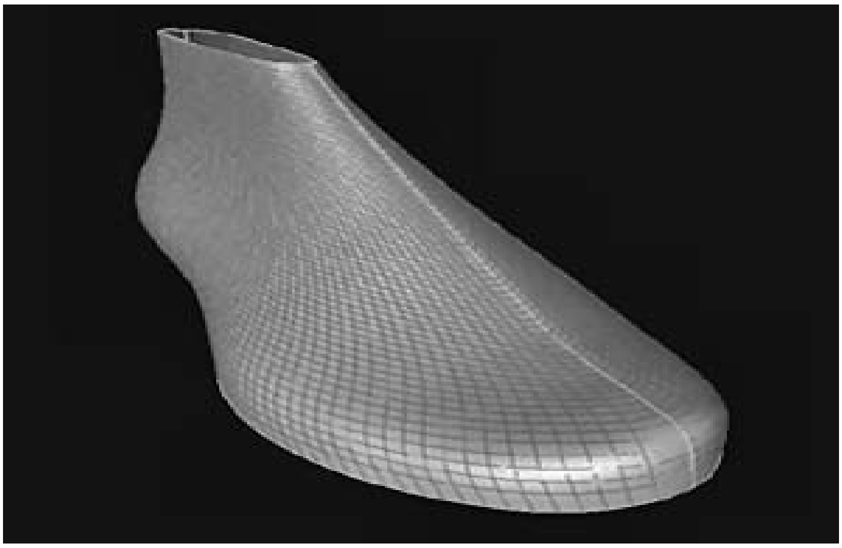


Figure 4. Surface Model of a Last

4. Feather edge creation

The feather edge is nominally represented by a sharp edge and this poses a problem as sharp edges (or edges with very small radii) will not be detected by the digitisation process. The initial approach adopted for the creation of feather edge boundary curves was based on the process of manually tracing these features on actual shoe lasts (figure 5). This process was time consuming and inherently approximate as it relied on the operators skill to detect and trace complex curves which may well be ill defined on the physical model. Another approach has been developed, as part of this project, where no extra device and no extra measurements are required.

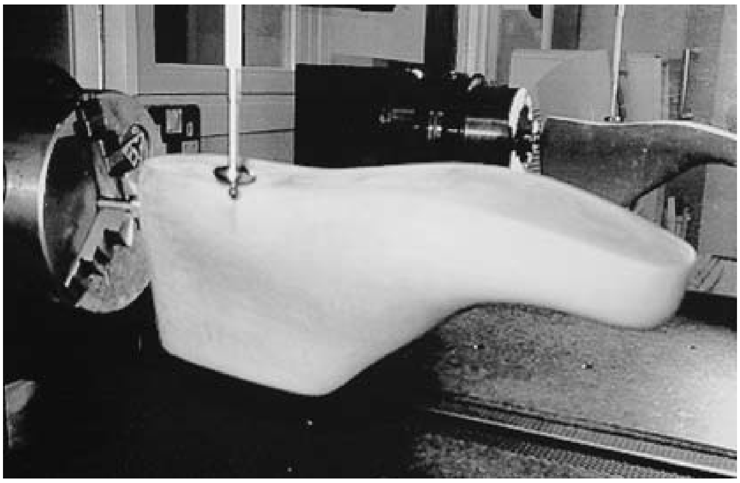


Figure 5. Manually Tracing a Feather Edge

4.1 The automatic creation of feather edges.

The contact scanning system used to digitise soles and lasts develops data along cross-sectional paths known as scan lines. These may be linear or radial, depending on the topology of the scanned part, and they define a grid pattern over the whole surface being scanned. Hence, scan lines impose a basic structure on the point-cloud data set defining a scanned object.

The procedure for creating feather edges utilises these scan lines. Consecutive vertices along these are considered to be connected by linear edges (Figure 6). The scalar product is then used to determine the angles subtending each and every consecutive pair of edges (**θ_n and θ_{n+1}**). These angles are stored in an array and compared with a user defined threshold value. If two consecutive angles on the scan line are found to be less that this threshold it is assumed that a feather edge has been crossed. The nominal position of the edge is then estimated by constructing a perpendicular bisector through the edge lying between the pair of angles (**θ_n and θ_{n+1}**) and constructing a circular arc centered on this and passing through the vertices (**V_n and V_{n+1}**) at either end. The point where the bisector intersects the outside of this circular arc (**V_c**) is then assumed to lie on the feather edge. This procedure is repeated for every scan line on the digitised model and the resulting set of feather edge points is stored in an array.

The feather edge array is refined by applying the following rules:

a. A radial scan line will result in only one feather edge crossing.
b. A linear scan line will result in only two feather edge crossings.
c. If the expected number of feather edge crossings is exceeded, then take the 'sharpest' (i.e. the one with the smallest pair of angles).
d. If less than the expected number of crossings is detected, then decrease the threshold values and repeat the procedure.

This process provides a list of data points lying on the feather edge, it is then a simple matter to fit a boundary curve through these points and export this to a CAD package. The equations required to fit surfaces through points are held in specific routines provided by the Renishaw Tracesurf software. Both the cloud of data points and the boundary curve are exported to this software and the feather edge is used as a boundary line for the purposes of segmentation (section 3.2). The constructed feather edge defines the limits of the first surface patch and the **C^0** continuity condition is applied between this and all adjacent patches on the last model, giving a nominal sharp edge corresponding to the constructed feather edge. Experimentation has shown that this can result in considerable time saving when compared to manually tracing feather edges, even in the case of a last with ill defined edges. It has also been shown that the proposed method has proved to be more accurate than equivalent manual methods of feather edge creation.

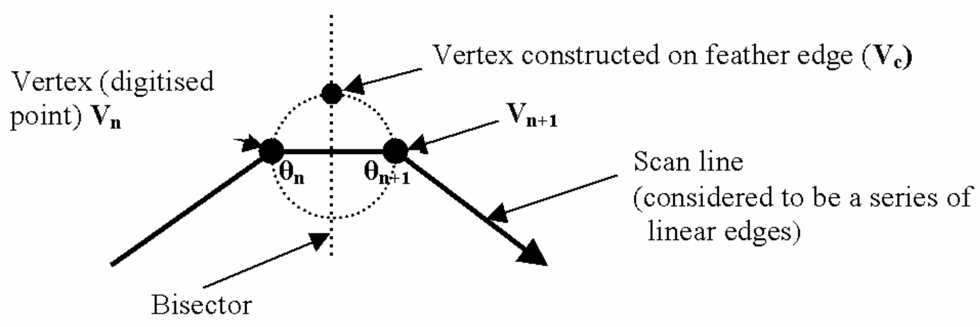
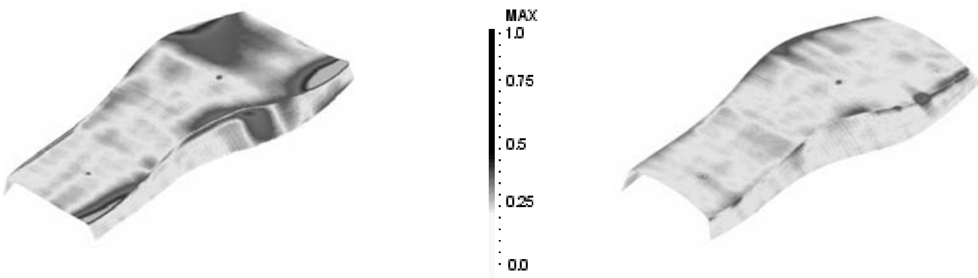


Figure 6. Scan Line and Bisector

4.2 Evaluation of the proposed method

In order to test the edge creation technique, the bottom part of the last was chosen as a sample. A CAD model was then constructed using two different methods. One has been built using manual edge creation, the other used the proposed automatic techniques for feather edge creation. The distance between every digitised point and the corresponding point on the modelled surface was calculated and a gray scale was applied to visualise the accuracy of the whole model. The point with the highest error was also determined and displayed (figure 7). It can be seen on the manual model that areas of high inaccuracy appear near the high changes of continuity, that is around the feather edge.The second model clearly shows that the error can be reduced considerably by using the proposed edge creation method.



Manual edge detection, maximum error : 2.1mm

Automatic edge detection, maximum error : 0.6mm

Figure 7. Comparisons of Edge Detection Methods

5. Implementation

This project commenced at a point in time when wooden lasts and wax models of soles were being transported to South America and the Far East in order to covey design concepts to manufacturers. This was expensive and time consuming, particularly when manufacturing specifications were changed to accommodate design revisions. Typical lead times from design concept to finished product were in the region of twelve weeks.

The proposed reverse engineering methods facilitated the generation of fully surfaced last models complete with feather edge, in a period of three to four hours. Triangulated models of soles were generated in six to eight hours. The longer period for soles being due to the higher density of scanned data needed to define surface texture. These models could be transmitted around the world very rapidly and at minimal cost. Design and manufacturing revisions were easily facilitated and the whole process of product development became faster and cheaper. An additional advantage was that these geometric models could be used to generate STL data for prototype parts using stereo lithographic modelling equipment. Adoption of these methods helped to reduce design concept to finished product lead times to four weeks.

The benefits of reducing lead time by eight weeks have not been fully quantified, but it is generally accepted that getting products to market two months sooner gives an added competitive edge to the shoe manufacturer, resulting in increased sales of particular shoe styles. There are also considerable cost benefits associated with the reduced storage and transportation costs associated with CAD models rather than real, physical models of soles and lasts.

6. Conclusions

Contact scanning with digital probes has been shown to be effective for the digitisation of both textured and smooth parts. Digital probes with small radii were found to be particularly effective for the collection of surface texture data. The soles of shoes can be adequately described by triangulated surfaces, but lasts require fully surfaced representations with boundaries corresponding to the feather edge.

A new technique for the automatic creation of feather edges on shoe lasts has been proposed and evaluated. This is based on the construction of feather edges from scan lines on point cloud data sets. It has been shown that this method can be employed for the segmentation of scanned point-cloud data and that it is both quicker and more accurate than manual feather edge detection methods.

It has also been shown that reverse engineering techniques can be utilised in the footwear industry to facilitate rapid product development and support manufacturing activities at remote sites. Three-dimensional point-cloud data can be captured from physical concept models using commercially available digital scanning systems and accurate geometric surface models of lasts and soles has been generated directly from point-cloud data sets obtained from hand-made wooden and wax masters. Key manufacturing features, such as surface textures and feather edges, have been incorporated into these models. The models can be easily transmitted to manufacturing companies in other countries, and concept to market lead times have been reduced by up to two-thirds in this case study.

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