RESIZABLE OUTERWEAR TEMPLATES FOR VIRTUAL DESIGN AND PATTERN FLATTENING

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SCHOOL OF MATERIALS

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LIST OF ABBREVIATIONS, SYMBOLS AND UNITS

Abbreviation	*Full Name*
2D	Two-dimensional
3D	Three-dimensional
APGS	Automatic Pattern Generation System
BS	British Standard
CAD	Computer-aided Design
CAESAR	Civilian American and European Surface Anthropometry Resources
CBI	Centre for the Promotion of Imports from Developing Countries
DCTT	DesignConcept TexTech
DSSP	Digital Shape Sampling and Processing
EN	European Norm
FAST	Fabric Assurance by Simple Testing
HC3D	Haute Couture 3D
HP	Hewlett-Packard
GS	Geomagic Studio
IGES	Initial Graphics Exchange Specification
ISO	International Organisation for Standardisation
KES	Kawabata Evaluation System
LED	Light-emitting Diods
MS	Microsoft
M&S	Marks & Spencer
n.d.	No Date
NURBS	Non-Uniform Rational B-Spline
PHG	Parametric Human Generator
PPA	Parametric Pattern Accelerator
PPG	Parametric Pattern Generator
RAM	Random Access Memory

rbd	Reduced Body Data
RE	Reverse Engineering
[TC]²	Textile/Clothing Technology Corporation

Symbol	***Meaning***
º	Angle in degrees
<	Less than
€	Euro

Unit	***Full Name***
cm	Centimetre
g	Gram
GB	Gigabyte
GHz	Gigahertz
m	Metre
mm	Millimetre

ABSTRACT

The aim of this research was to implement a computer-aided 3D to 2D pattern development technique for outerwear. A preponderance of total clothing consumption is of garments in this category, which are designed to offer the wearer significant levels of ease. Yet there has not previously been on the market any system which offers a practical solution to the problems of 3D design and pattern flattening for clothing in this category. A set of 3D outerwear templates, one for men's shirts and another for men's trousers, has been developed to execute pattern flattening from virtual designs and this approach offers significant reduction in time and manpower involvement in the clothing development phase by combining creative and technical garment design processes into a single step. The outerwear templates developed and demonstrated in this research work can provide 3D design platforms for clothing designers to create virtual clothing as a surface layer which can be flattened to create a traditional pattern.

Point-Cloud data captured by a modern white-light-based 3D body-scanning system were used as the basic input for creating the outerwear templates. A set of sectional curves, representative of anthropometric size parameters, was extracted from a virtual model generated from the body scan data by using reverse engineering software. These sectional curves were then modified to reproduce the required profile upon which to create items of men's outerwear. The curves were made symmetrical, as required, before scaling to impart resizability. Using geometric modelling technique, a new surface was generated out of these resizable curves to form the required 3D outerwear templates. Through a set of functionality tests, it has been found that both of the templates developed in this research may be used for virtual design, 3D grading and pattern flattening.

DECLARATION

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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DEDICATION

To My Parents:

Md. Abdul Hamid and Shamsunnahar Hamid

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Chapter 1: Introduction and Background to the Research

1.1 Clothing Design and Development Techniques

Clothing development includes both creative and technical design of a garment targeted for an identified consumer or a set of consumers (Glock and Kunz, 2000). The creative design aspect covers the process of fashion design whereas the technical design aspect covers the creation of pattern pieces based on the size information of the target consumer or consumers in order to facilitate the cutting of the fabrics from which the clothing is to be made. These two distinct aspects of clothing design process are usually handled separately by different professional individuals namely fashion designers and pattern technicians or tailors. Figure 1-1 presents a generic clothing design process practised in the industry today. Both manual and computer-based techniques, either in two-dimensional (2D) or in three dimensional (3D) formats, are being used in the industry for the product-development functions of both tailor-made and ready-made garments.

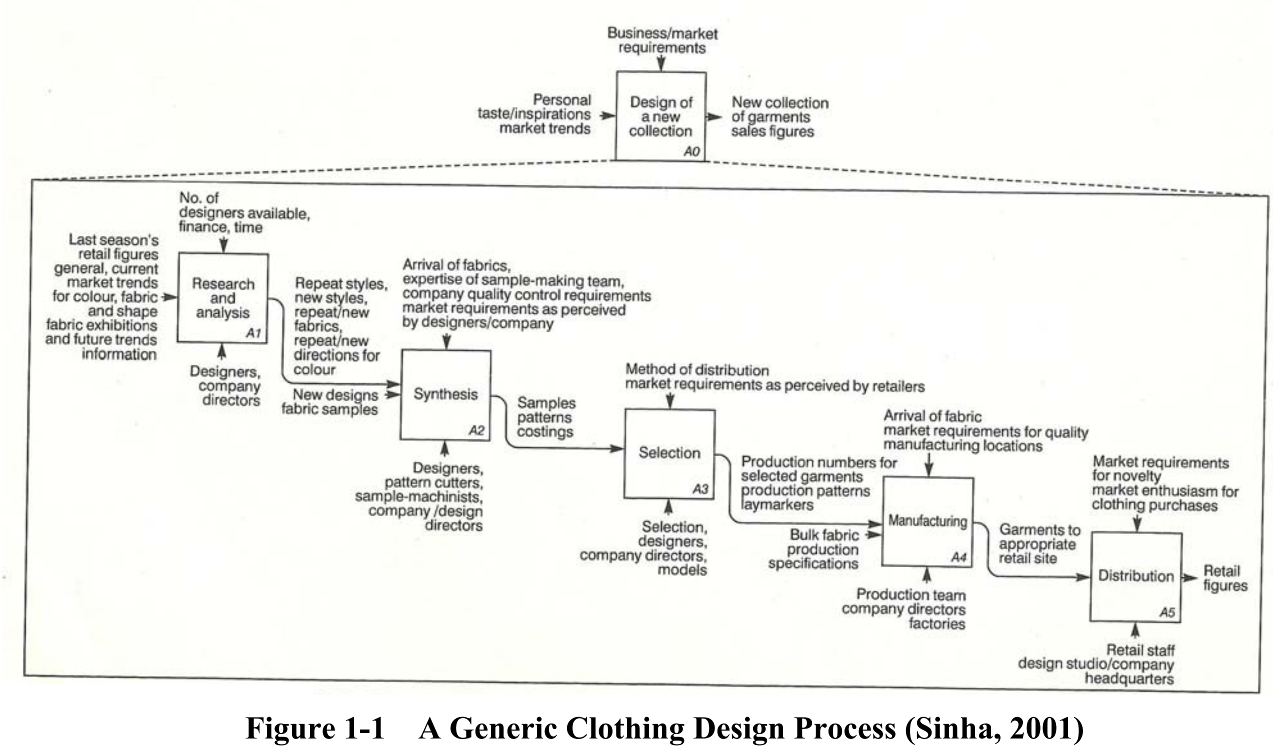


Figure 1-1 A Generic Clothing Design Process (Sinha, 2001)

1.1.1 Manual Techniques

In the clothing development process, a tailor or a pattern technician converts the initial design in the form of pattern pieces, after incorporating the size data, ease and seam allowances and other information necessary for the subsequent production process. There are three fundamental approaches to pattern creation that have been in practice in the clothing industry over a very long period of time and are still in current use. These are 3D draping (also known as the *"haute couture"* process), block pattern development and pattern drafting (Chi, 2005; 2007).

In the 3D draping or modelling process (*haute couture*), an intermediate garment known as 'toile' is produced by moulding, cutting and pinning or sewing an inexpensive fabric, usually calico, on to a body form (a mannequin, or directly on to a human body). The toile is then cut off the body form to produce the flat pattern pieces which may then have ease and seam allowances added to them. This process is time-consuming, but ensures a good fit and flattering drape, as the 3D body geometry is taken into account. This technique is usually used for high-priced tailor-made garments.

Pattern drafting is the engineered version of pattern creation, and has proven to be most suitable for targeting the mass production of garments based on standard average size measurements. The drafting process covers the geometrical drawing of patterns using the size measurements of seen or unseen customers together with relevant fabric information. This process is thus highly dependant on the expertise of the pattern technician to ensure an acceptable fit of the garments on either an individual client, or as a standard size intended for bulk production. In most cases the mass-production process involves making prototype garments based on the first drafts of patterns, and having at least one, but more commonly, several fit trials on live models or on a standard mannequin in order to rectify and finalise the patterns even if the size chart and ease allowances are followed correctly. This is because the process does not encompass the 3D geometry of the human body as does the fabric draping method. Generally patterns are made for a base size within a size range; once finalised, they are then proportionally enlarged or reduced into bigger or smaller sizes in the range. This process is known as grading.

Block patterns are constructed to fit an average figure (Aldrich, 1990). This approach is derived from the *haute couture* process but instead of making a toile for each individual, a series of block patterns is created from cardboard to represent the average figures within a standard size grouping. So, several sets of graded block patterns are required for each type and style of garment, in order to cover an appropriate range of sizes. These block patterns are then preserved as sets of standard, congruent, pattern pieces. The tailor, whenever necessary, selects an appropriate set of block pattern pieces closest to the body size of a customer and applies essential adjustments (such as sleeve length, hem position and length of leg) on them (usually by chalking on the fabric) to produce customised garments. Once a full range of block patterns has been created, it becomes a faster process to serve every individual customer, but the tailor's expertise in customising the patterns for each individual plays a critical role to make each garment fit well. Variations to traditional block pattern development are commonly used in the clothing industry and can include features of both 3D draping (*haute couture*) and geometrical pattern drafting. Examples of drafting block patterns geometrically for use as a basis pattern for interpreting a design have also been published (Aldrich, 1990).

1.1.2 Computer-based Techniques

Computer-based solutions are available for fashion drawing and pattern creation. Today's industry prefers to use more and more computer-based techniques as they offer efficiency and time-saving solutions to many complicated tasks and they also facilitate Internet-based communication between one country and almost any geographically remote corner of the world. General graphics software packages such as Illustrator® from Adobe Systems Incorporated (USA) and CorelDRAW® from Corel Corporation (Canada) or more customised packages for the fashion industry such as Kaledo® Style, Kaledo® Collection, Kaledo® Knit, Print, Weave from Lectra (France), Vision® fashion studio from Gerber Technology (USA), Tex-Design™ from Koppermann Computersysteme GmbH (Germany) are being extensively used around the world for clothing development (Sayem, Kennon and Clarke, 2010). Specialised CAD (Computer-aided Design) software packages for drafting and grading flat patterns were introduced into the clothing industry in the 1980s (Burke, 2006) and they have become very popular within the industry. Today a number of 2D clothing CAD systems are available on the market for use in geometrical pattern drafting from first principles using anthropometric information of the target size and shape. Commonly known software packages within this group are: *cad.assyst* from Assyst (Germany), *Modaris* from Lectra (France), *Accumark* from Gerber Technology (USA), *PAD Pattern Design* from PAD System Technologies Inc. (Canada), *TUKAcad* from Tukatech (USA), *GRAFIS* from Software Dr. K. Friedrich (Germany), *Audaces Apparel Patterns* from Audaces (Brazil), *COAT* from COAT- EDV-Systeme (Germany) and *Fashion CAD* from Cad Cam Solutions (Australia) (Sayem, Kennon and Clarke, 2010). In addition to pattern drafting, it is also possible to input existing block patterns with the help of a "digitiser" into virtually any of the currently available software packages. Usually they also support automatic pattern grading with the help of pre-developed grade rule tables. Techniques are also available to drape digital pattern pieces on virtual mannequins to create virtual clothing (Fozzard and Rawling, 1991; 1992; Okabe et al., 1992; Volino et al., 1996; Kang and Kim, 2000b; 2000c; Chiricota, 2003; Fuhrmann et al., 2003; Thalmann and Valino, 2005; Luo and Yuen, 2005). This technology has already reached a stage of sufficient maturity to be implemented in the industry and several clothing CAD systems that include virtual mannequins and drape engines are available on the market (Sayem, Kennon and Clarke, 2010; 2011). 3D software packages such as *Vstitcher* from Browzwear (Israel), *Accumark vstistcher* from Gerber (USA), *Haute Couture 3D* from PAD system Technologies Inc. (Canada), *Modaris 3D FIT* from Lectra (France), *efit Simulator™* from Tukatech (USA), *3D Runway* from OptiTex International (Israel) and *Vidya* from Assyst (Germany) facilitate the wrapping of 2D pattern pieces onto a virtual human model and enable the simulation and validation of styles, fabrics, motifs and colour ranges. They also allow pattern designers to check garment fit in various fabrics and sizes and they facilitate the virtual review of prototype garments.

An emerging technique for pattern creation is that of "3D to 2D pattern unwrapping" which means the automatic generation of 2D patterns by unwrapping or flattening the 3D design. Notable research has been carried out in this field in the last decade (McCartney et al., 2000; Kim and Kang, 2002; Wang, Smith and Yuen, 2002; Wang Wang and Yuen, 2002; Sayem, 2004; Petrak and Rogale, 2006; Petrak, Rogale and Mandekic´-Botteri, 2006; Decaudin et al., 2006; Kim and Petrak, 2007; Fang and Ding, 2008; Fang, Ding and Huang, 2008). However this technology is not equally advanced and sufficiently mature for both intimate wear and outerwear to be implemented in the industry at this point in time. A few clothing CAD systems such as *3D Interactive software* from TPC (Hong Kong) and *3D Runway* from OptiTex International (Israel) provide the capability to execute pattern unwrapping, but in a very limited context and only for close-fitting garments. No efficient solution is available for outerwear, which encompasses the major portion of clothing consumption worldwide. For example, it was 88% of total clothing consumption in the 27 member states of the European Union in 2007 and worth of € 260 billion (CBI, 2008).

1.2 Background to the Research

Many European and American clothing retailers have chosen offshore sourcing and production strategies to enjoy the advantages of labour market differentials in many lower labour cost countries (Christerson and Appelbaum, 1995; Firoz and Ammaturo, 2002; Gereffi and Memedovic, 2003). As a consequence of this phenomenon, the majority of the world’s clothing production currently takes place in countries which are usually far away from European and American clothing retailers. Due to this geographical distance between manufacturer and retailer, the process of physical prototyping according to a designer’s specification and then the transportation of prototypes to the retailers takes a significant length of time. Repetition of this process, whenever necessary in order to rectify any problems related to assembly or fit or to incorporate any change in design, together with the distance involved inevitably increases the development lead time and cost even further. However there is always pressure from the retailers’ side to curtail the development lead time and to minimise the cost involvement in physical prototyping in order to cope with rapid fashion changes and business competition. A solution to this problem could be virtual prototyping utilising the developments in computer graphics and software technologies. Using available 3D CAD software systems it is now possible to drape 2D drafted pattern pieces on a virtual mannequin and simulate the 3D appearance of the clothing realistically. This gives the opportunity of identifying flaws in 2D patterns through a process of virtual fit checking in order to rectify initial problems with 2D pattern pieces without any need for a physical prototype with real materials. As the process of virtual fit checking can also be communicated over the Internet platform between suppliers and retailers from any corner of the world, virtual prototyping can significantly shorten the product-development lead time and reduce the dependency on physical prototypes, as claimed by the software suppliers (Ernst, 2009; Lectra Bylined Article, n.d.; Tukatech, n.d.).

The use of CAD systems for 3D garment visualisation from 2D patterns has recently been started in the clothing industry. However, industrial application of any 3D to 2D pattern unwrapping technique is yet to be made, due to the non-availability of an appropriate CAD system on the market. The use of 3D to 2D pattern unwrapping techniques will usefully abbreviate the development process in more than one respect. It will offer to combine fashion drawing and pattern drawing into single step as flat patterns can be extracted automatically from 3D designs avoiding any need for 2D drafting. It will also cut the time and manpower involvement significantly in a way that will provide a significant commercial advantage. To realise this concept in practice, the CAD system must be able to flatten the 3D surface of a garment into 2D and should have a sketch-based interface to accommodate the requirements of the designers. To be used in the mass production clothing industry, it is essential for such a system to offer at least the following components:

a) resizable 3D design platform for both bodywear and outerwear, on which a virtual garment can be created and suitably graded to into different sizes;

b) 3D drawing and surface generation tools;

c) ‘3D to 2D’ surface flattening tools.

Such a CAD system is yet to be made available on the market. Most of the available 3D clothing CAD systems come with virtual mannequins to drape 2D pattern pieces on to them but do not include any flattening modules. A few software packages with integrated flattening tools offer a virtual mannequin as a 3D clothing design platform but only for close-fitting garments. They offer no solution for outerwear, which holds the lion’s share of clothing market. McCartney et al. (2000), Hinds and McCartney (2000), Kim and Kang (2002), Wang, Smith and Yuen (2002), Decaudin et al. (2006), Petrak, Rogale and Mandekic´-Botteri (2006), Kim and Park (2007), Fang and Ding (2008) demonstrated various techniques for developing virtual clothing directly on a virtual mannequin and finally flattening it into 2D pattern pieces. However, none of their techniques has been proven to be well suited to designing outerwear efficiently.

1.3 Research Problem and Proposed Solution

Available pattern draping technology can simulate both close-fitting and loose-fitting garments on virtual mannequins. However for the purpose of effective pattern unwrapping, a design platform is required to produce virtual clothing in the form of a developable surface that can be flattened into 2D. As outerwear does not assume the exact geometry of the human body at all places, a precise virtual model of a human body does not work effectively as a design platform in this case as it does for close-fitting garments. While following the broad architecture of the wearer's body and satisfying fit and comfort requirements, outwear includes a variable gap between the body and the garments. This gap is known as "ease" in terms of clothing science and this can be incorporated into a garment either for the promotion of the wearer's comfort and performance or for the realisation of versatile design features such as a non-body dependant silhouette of a garment. Within the range of commercial pattern unwrapping systems, precise virtual mannequins are not effective enough for the incorporation of design ease and for the development of a non-body dependant silhouette of a garment. With their only effective use for close-fitting garments, the pattern unwrapping technique has so far found no industrial application. The available solutions that are discussed in detail in the next chapter are also not very interesting from either the designers' or the clothing professionals' point of view. A simple sketch-based interface, which can be resized using size parameters and which will offer a platform upon which to create virtual outerwear as a surface suitable for flattening into 2D, is proposed within the framework of this research work as a solution to this problem.

A 3D template is hypothesised in order to develop such a sketch-based interface for designers to create virtual outerwear. This 3D template will be developed based on Point-Cloud data captured by scanning human models. However, the scanned data will be processed and modified in such a way that the resultant structure will take into account the structure and silhouette of a particular item of outerwear. Instead of having a common platform for both upper body and lower body outerwear, specific 3D templates separately for upper and lower body garments are suggested here. In order to incorporate ease directly into 3D designs, it is suggested that it should be included into the proposed 3D template by identifying the most important girth and displacement measurement areas so that they may be modified or resized with the help of a size database which includes appropriate functional and design eases. As a result, the outwear design developed as a layer of a surface adjacent to the 3D template will have the required ease automatically included into it. It is anticipated that such a product-specific 3D template should provide an efficient design platform for the development of virtual outerwear using drawing and mesh generation tools available in a CAD system; and after linking with the pre-developed size database, it will facilitate the integration of appropriate levels of ease as per the designer's and the wearer's requirements. It will be appreciated that coupling the size database with the 3D template will also provide an option for automatic grading in 3D. When a flattening tool is available within the environment of a 3D CAD system, the virtual clothing designed on such an outerwear template may be flattened into 2D pattern pieces, thus making available the capability of 3D to 2D pattern flattening for outerwear.

1.4 Objectives

The aim of this research is to develop a set of resizable templates, as 3D drawing and designing interfaces, to execute 3D to 2D pattern unwrapping of outerwear. It is intended to demonstrate a CAD technique to develop two templates, one for men's upper body garments and another for lower body garments, and to demonstrate the development of virtual outerwear by 3D drawing and surface generation, extraction of 2D pattern pieces using flattening techniques and 3D grading with the help of a size database.

1.5 Research Rationale

The combined techniques of 3D design, 3D grading and extracting 2D patterns for loose-fitting garments have not been demonstrated in a usable and practicable format for the clothing industry. As a consequence of this, no customised CAD software packages for the 3D to 2D pattern unwrapping of outerwear products are available on the market. Creating virtual garments directly on 3D virtual templates using the drawing tools and then extracting 2D pattern pieces to input into the subsequent production processes, has significant implications for the clothing industry. It will not only shorten the product-development process by combining fashion drawing and pattern creation into a single step, but it will also make pattern creation a skill-free task, contrary to existing techniques.

1.6 Scope and Limitations

This research attempts to combine modern anthropometric techniques with available reverse engineering and CAD techniques for the development of a novel design template for outerwear to facilitate pattern flattening and 3D grading as well as 3D drawing. This work paves a way for the successful implementation of pattern unwrapping techniques in the ready-made garment industry through the development of product-specific templates for outerwear. The process demonstrated within the framework of this research provides an effective guideline for software developers for developing 3D design interfaces for both male and female outerwear although this work is primarily limited to the development of two different types of men's outerwear templates for the purpose of demonstration.

This research does not include any sizing survey to identify the standard average body for a size group. As a result the developed 3D templates cannot be considered as fully representative to concurrent populations of any ethnic origin. However the demonstrated procedures can easily be implemented for developing standard templates for any size group of a demographic population, utilising the datasets from the latest anthropometric surveys, for example SizeUK, which covers 3D shape analysis of selected population subsets categorised by age, region, socio-economic group or ethnicity (SizeUK; n.d.).

1.7 Thesis Structure

This thesis consists of in total seven chapters. The experimental part is split into two chapters (chapter 4 and 5) considering the types of product they address.

Chapter 1: Introduction and Background to the Research. Being the gateway chapter of the thesis, this chapter has highlighted an existing problem and limitation in the area of virtual clothing flattening and indicates a way of addressing this through scientific methods. This has also laid the foundation of this research work by briefly introducing the prevailing techniques in clothing design and development, the trend of development in this area and putting forward the aims and objectives of this research.

Chapter 2: Literature Review. This chapter includes seven subsections covering different approaches to 3D clothing design and their historical development, the use of virtual mannequins as design templates, a summary of available 3D systems for clothing design, the advantages of virtual clothing, body-scanning and the latest sizing surveys and other areas interconnected with clothing design such as ease and pattern grading.

Chapter 3: Research Methodology. The methods selected and applied are detailed here. The construction and application of the body-scanning system used are described in depth. The applications of software programs for performing the major tasks are also explained in detail. The computer system and machines and materials used in this research work are also outlined in this chapter.

Chapter 4: Resizable Shirts Template. The step by step procedure followed and developed for creating the proposed template for a men's shirt and related upper body outerwear is described in this chapter. This chapter also covers the tasks performed to test the functionality of the resizable shirt template developed within the framework of this research.

Chapter 5: Resizable Trousers Template. Similarly to the previous chapter, this section details the steps and procedure followed and developed to produce a resizable trouser template.

Chapter 6: Results and Discussion. The outcomes of the functionality tests performed on the shirt and trouser templates that have been developed are discussed in this chapter. Limitations of the templates are highlighted and the ways to overcome them are explained. An outline of a next generation clothing design system is also presented in this chapter.

Chapter 7: Conclusions and Recommendations. This chapter concludes the thesis with a brief summary of the work and its outcomes. It also highlights some areas of further work as recommendations.

Chapter 2: Literature Review

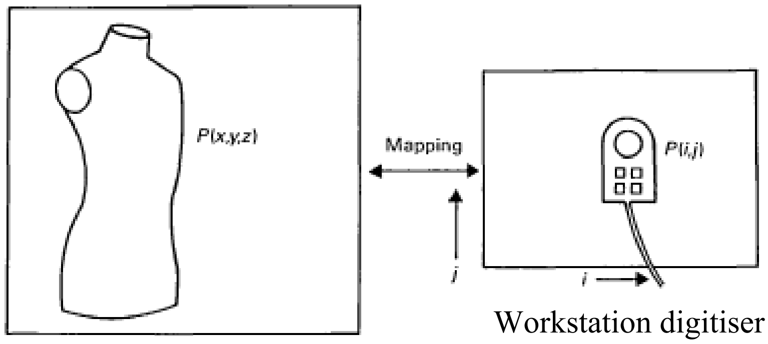
2.1 Computer-aided 3D Clothing Design

Review of the published literature has identified six distinct approaches to 3D clothing design on which research work has been performed in the last two decades. They are: 1) 3D modelling and 2D pattern unwrapping; 2) 3D simulation of 2D patterns; 3) 2D-sketch-based 3D simulation; 4) combined techniques; 5) reactive 2D/3D design technique; and 6) digital draping. These various approaches will be considered systematically in the following sub-sections.

2.1.1 3D Modelling and 2D Pattern Unwrapping

The 3D modelling and 2D pattern unwrapping approach produces virtual clothing in space, most commonly using a virtual body as a platform on which 3D clothing development can be performed, and it generates 2D pattern pieces from the 3D designs using a surface flattening tool. According to Yunchu and Weiyun (2007), there are two typical methods for surface flattening, namely: geometrical flattening and physical flattening. Geometrically-based flattening methods develop planar surfaces by mapping 3D surfaces, constrained only by geometrical conditions; they do not consider any forces or energy levels. Whereas physically based methods consider various forces or energies during the process of surface flattening.

One of the early processes for developing 3D garments directly on a virtual mannequin is presented by Hinds and McCartney (1990) and Hinds et al. (1992). They used a virtual mannequin, developed by digitising a tailor's dummy, as a design interface on which to specify 3D garment panels and a digitiser as an input device for drawing garment panels on the virtual mannequin as can be seen in Figure 2-1. With the help of a designer's interaction, the early version of their CAD system could develop and visualise 3D garment design which could automatically adapt the dimensions and surface geometry of the virtual mannequin for use on the work station. It did not require the designer to insert the dimensions of the garments into the system. The authors also hinted at the possibility of extracting flattened patterns from the 3D design using their CAD system but did not demonstrate it in their early publications.



Workstation digitiser

Workstation screen

Figure 2-1 Workstation Screen and Digitiser of the 3D CAD System by Hinds and McCartney (1992)

Later McCartney et al. (2000) and Hinds and McCartney (2000) described a 3D CAD system that could flatten 3D garment panels into 2D pattern pieces. Their (Hinds and McCartney, 1990; Hinds et al., 1992; Hinds and McCartney, 2000; McCartney et al., 2000) design process was particularly suitable for close-fitting garments but followed a laborious route to incorporate variable ease at different places between the virtual body and the garment panels for outerwear. It required designers to specify the offset manually along the edges of each garment panel while recreating it to incorporate variable ease as required at the specified places. This made the technique onerous for designing loose-fitting garments. Furthermore, their process included no option for resizing the mannequin and also provided no option for automatic grading in a 3D format.

Kang and Kim (2000a) and Kim and Kang (2002) demonstrated a system of designing 3D clothing on virtual body models and a subsequent technique of 2D pattern flattening. They (Kang and Kim, 2000a) used a sliding gauge to capture anthropometric data and reconstructed the body model virtually in the cylindrical coordinate system using those data. To generate a virtual garment model, they primarily drew the garment panels as a set of rectangular meshes on a physical dummy manually using black marking tape as can be seen in Figure 2-2; and then captured the 3D shape of the mesh network using a stereoscopic technique which employed two CCD (charge-coupled device) cameras to input into their CAD system. After successive image processing stages and following the application of mathematical modelling techniques, the virtual garment was fitted onto the body model. Once the fitting was found to be appropriate, the garment was subsequently flattened into 2D pattern pieces using their pattern flattening algorithm. In 2002, they (Kim and Kang, 2002) used body scan data to generate a virtual body model and a similar stereo-vision technique to input garment panels as mesh structures into their system. The mesh structure of the garments panels was then fitted on to the body model using their own surface wrapping algorithm and subsequently flattened into 2D patterns using their own planar pattern mapping algorithm. Their work (Kang and Kim 2000a; Kim and Kang 2002) is a good example of the application of the stereo-vision technique for garment model generation. However it is unlikely that it currently finds any application in the clothing industry, as it involves the manual work of mesh marking on a physical mannequin, the use of stereo-vision techniques and it also does not shorten the design process in any way.

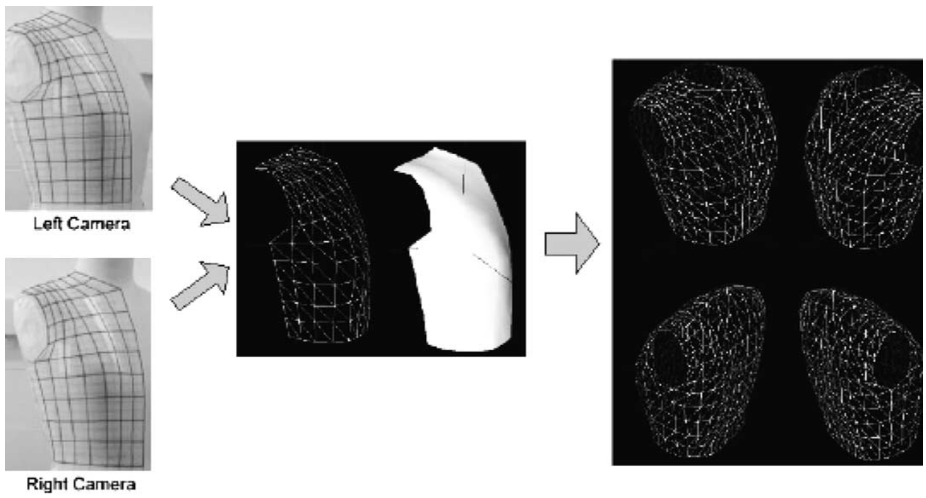


Figure 2-2 Virtual Garment Model by Kim and Kang (2002)

Wang, Wang and Yuen (2002) presented a sketch-based 3D design platform using Visual C++ and the OpenGL library under the Windows NT/2000 operating system. Their system includes a set of pre-developed garment templates and virtual body models. They developed the garment templates as triangular mesh structures, which they named "*garment feature template*" (Figure 2-3). In the next step, they fitted the garment template onto a virtual body model to develop a 3D clothing design platform on which a garment profile could be specified. They demonstrated the specification of the 3D garment profile on the "*garment feature template*" using 2D lines, regeneration of the mesh surface to represent the desired 3D design and unwrapping of the 2D pattern pieces. However, this process did not provide enough flexibility of 2D drawing on the 3D virtual model, as the 2D lines were constrained to the vertices of the mesh triangles in a single plane only. They also presented a concept of 3D grading of patterns by constructing the same garment on differently-sized virtual human models. For 3D grading, the same garment has to be repeatedly constructed on different-sized virtual models, which is a very time-consuming and repetitive process. Later they (Wang, Wang and Yuen, 2005) improved their system by incorporating freeform modification tools such as "mesh painting" and "mesh cutting", but the system remained focussed on made-to-measure clothing only.

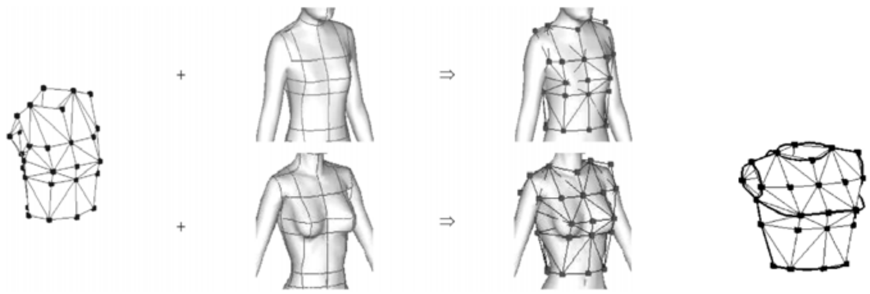


Figure 2-3 Fitting Triangulated Garment Template on Virtual Bodies, Specifying 3D Garment Profile using 2D Lines (Right) (Wang, Wang and Yuen, 2002)

Development of a parametric female model on which to create 3D designs of close-fitting garments and extraction of 2D flat patterns using an available CAD software package is demonstrated in the work of Sayem (2004). The benefit of the parametric model was experienced in the simple results of automatic grading of 3D shapes after incorporating size tables which were pre-loaded in the software as a database. Figure 2-4 shows the 3D design and 2D pattern pieces extracted from it and an example of automatically graded 3D shapes using this software. The research project 'AiF-1454 BG' from the German Federation of Industrial Research Associations which was concluded in 2007 also followed a similar approach for creating 3D designs of close-fitting garments on parametric virtual models and 2D pattern flattening (Roedel, 2008).

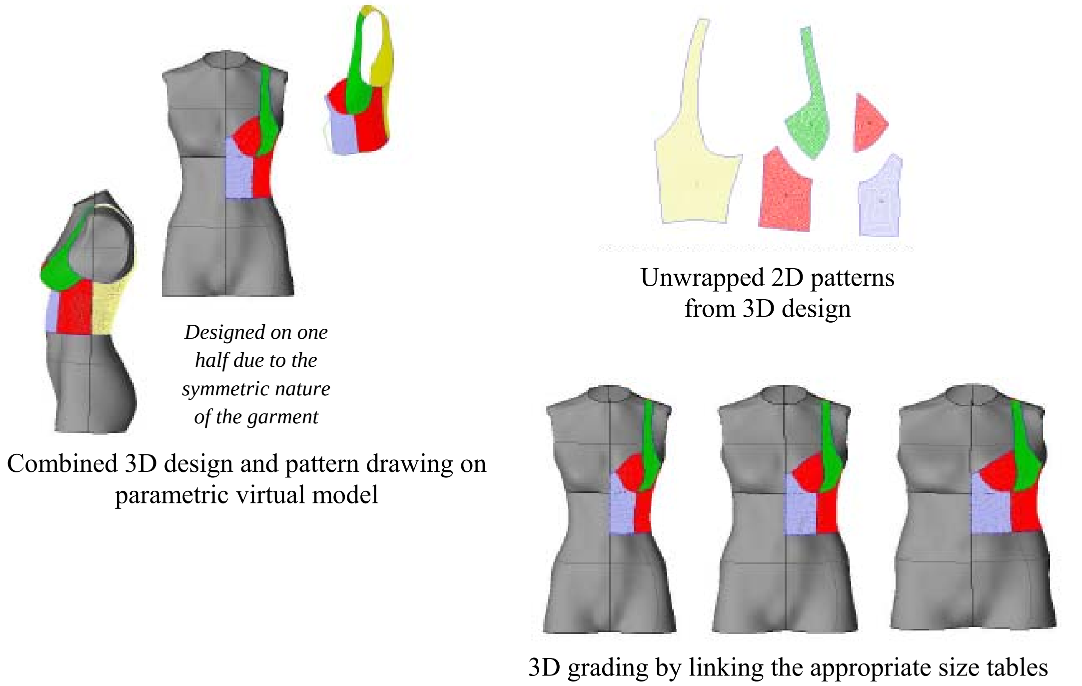


Figure 2-4 3D Design, 2D Pattern Generation and 3D Grading (Sayem, 2004)

Fang and Liao (2005a, 2005b) presented a CAD system which provided a mannequin-based interface and pre-designed garments parts. They developed the mannequin-based 3D garment designing and restyling tools using Microsoft foundation classes (MFS) and OpenGL by exploiting the mathematical formulae (Fang and Liao, 2005a; 2005b). Their system allows designers to position pre-designed garment parts on the mannequin and then modify those using 3D styling tools. Later Fang and Ding (2008) and Fang, Ding and Huang (2008) developed a pattern-flattening tool to further improve this system. They demonstrated the 2D flattening of patterns from 3D design (Fang and Ding, 2008) and visualisation of virtual clothing with different textures without considering the material properties (Fang and Liao, 2005a). As the designers can only work on pre-designed garment parts, their system limits the designer’s creativity during product development.

An interactive CAD system for drawing on the 3D mannequin, developing 3D designs from that drawing and subsequent flattening into 2D pattern pieces was described by

Petrak and Rogale (2006) and Petrak, Rogale and Mandekic´-Botteri (2006). They used the software suite "Rhinoceros 2.0" under the Windows 2000 operating system to develop the wireframe design of a garment, as shown in Figure 2-5, and to create a surface using cloth modelling technique. In the process of 3D design development, they (Petrak and Rogale, 2006) cut a virtual mannequin at different horizontal and vertical planes; and utilised the cut lines as seam lines and contoured them together with some characteristics points for developing a wireframe design of female clothing on it. With the help of a gridwork of curves they simulated front and back parts of a dress which were then flattened into 2D pattern pieces using the mathematical model of Petrak, Rogale and Mandekic´-Botteri (2006). Although their technique for 3D clothing design is very innovative, it does not sound very convenient for the designers to cut a virtual mannequin along numerous horizontal and vertical sections every time it is required to design a new style.

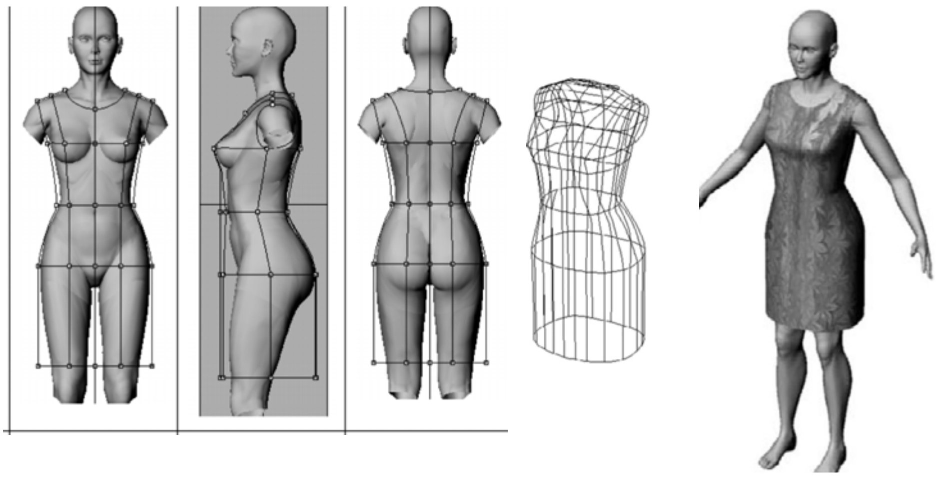


Figure 2-5 Wireframe Design of Garments by Petrak and Rogale (2006)

Kim and Park (2007) described a different technique for generating 3D designs in space and for developing 2D flat patterns from it. In their system, they divided a garment into two zones: a fit zone and a fashion zone. For fit zone modelling, they captured the surface of a physical mannequin using a multi-joint coordinate measurement system and reconstructed the mannequin's topography in the computer as shown in Figure 2-6. For the fashion zone they followed the CAD technique without considering the body geometry, rather considering the aesthetic appearance of the garment. Their system primarily focuses on individual fit garments. The use of a multi-joint measurement system for clothing design in the industry is not very promising from a fashion designer's point of view.

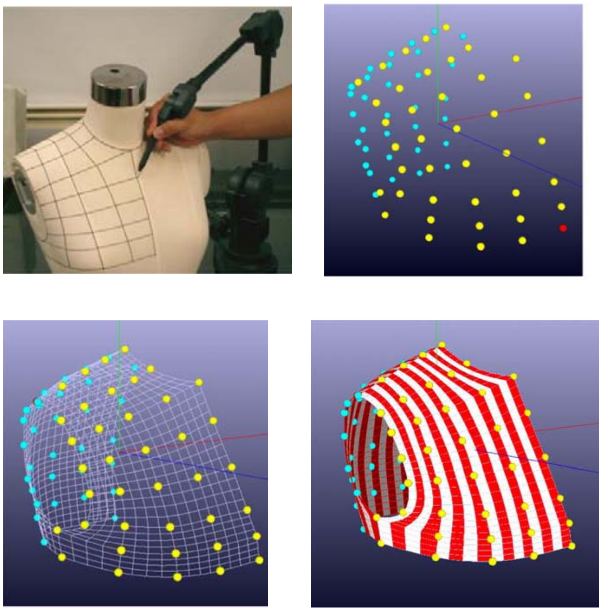
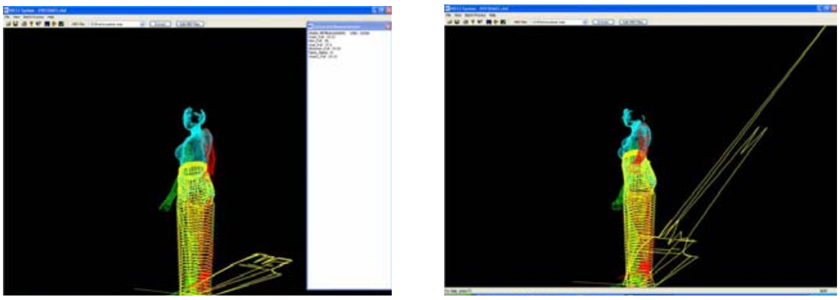


Figure 2-6 Fit zone modelling technique followed by Kim and Park (2007)

Yunchu and Weiyun (2007) defined clothing pattern outlines on a virtual mannequin and cut the mannequin surface within the pattern outline into 10 zones. Each zone was converted into a 3D wireframe following further sub-divisions. Finally they flattened the 3D wireframe of each zone into 2D. Their work features uniqueness, but is unlikely to be followed by clothing designers due to its complexity. Furthermore the process focuses on made-to-measure clothing only.

Smith-Outling (2007) utilised the 3D to 2D software available with the NX-12 scanning system from $[TC]^2$ (Textile/Clothing Technology Corporation) to demonstrate 3D to 2D pattern unwrapping of outerwear clothing. Although the software is primarily intended for processing body-scanned data to extract body measurements, it also allows users to define a garment on the 3D body image. It is reported by Smith-Outling (2007) that the 2D unwrapping process using this software occasionally resulted in incorrect 2D patterns (see Figure 2-7) and the physical prototypes realised from the correct 2D patterns showed some unacceptable fit problems. It is known from [TC]^2 that this application software is no longer in offer from them (Davis, 2011) [Email Communication].



(A) (B)

Figure 2-7 Correct (A) and Incorrect (B) Extraction of 2D Patterns by NX-12 System Demonstrated by Smith-Outling (2007)

Siegmund et al. (2010) determined the distance between body and garments using scan data at different points over the surface area of garments to generate horizontal and vertical offset curves relative to a virtual body. Utilising the offset curves, they demonstrated the designs of 3D trousers and a 3D jacket, which could also be flattened into 2D pieces using a flattening tool. Their process of ease definition by determining the distance of offset points is conceptually similar to that of Hinds and McCartney 1990, Hinds et al. 1992 and McCartney et al. 2000. Considering the offset distances as parameters to define the size and shape of outerwear is dissimilar to the established practices within the industry, which consider ease over girth measurements. It is apparent that it requires a lot of distance parameters to define the shape of a garment accurately if the 3D design is to be based on offset curves.

2.1.2 3D Simulation of 2D Patterns

3D garment simulation from 2D pattern pieces using virtual sewing and drape simulation techniques is a “2D to 3D” approach to 3D clothing design. Notable work that has successfully implemented this design approach includes research presented by Fozzard and Rawling (1991, 1992), Volino et al. (1996), Kang and Kim (2000b, 2000c), Chiricota (2003), Fuhrmann et al. (2003), Thalmann and Volino (2005) and Luo and

Yuen (2005). In the environment of 3D CAD systems that capitalise on this approach, the flat pattern pieces are placed on a virtual body and are joined together to produce virtual clothing as can be seen in Figure 2-8.

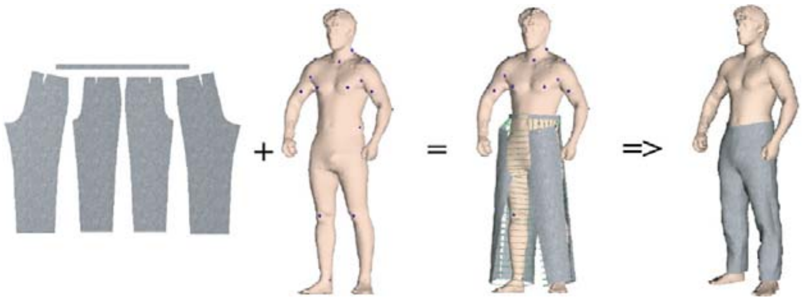


Figure 2-8 2D to 3D Design System by Fuhrmann et al. (2003)

A fabric modelling technique plays a key role in the garment simulation scheme. Mathematical modelling of fabrics began in the 1930s with the pioneering work of Peirce (1937). Attempts at the computer-aided modelling of fabrics were initiated in the late 1980s (Ng and Grimsdale, 1996; Choi and Ko, 2005) and a number of modelling techniques have been presented in the last twenty years. However, not all the techniques have been developed targeting an application in clothing design and simulation systems. A review of the different fabric modelling techniques can be found in Ng and Grimsdale (1996), Hardaker and Fozzard (1998), Breen (2000) and Fontana, Rizzi and Cugini (2005). The prevailing cloth simulation techniques can be classified into three categories: geometrical, physical, and hybrid (a combination of geometrical and physical).

Geometrical models look into the appearance and shape of the fabrics, particularly folds and creases, and represent them by geometrical equations. Mechanical properties of the fabrics are not considered in the geometrical techniques (Ng and Grimsdale, 1996; Hardaker and Fozzard, 1998 and Hunter and Fan, 2004). Physical modelling techniques consider the mechanical properties of fabrics which can be derived from the objective measurements. These techniques are more relevant for accurate CAD simulation of fabrics and comprise two approaches: energy-based techniques and force-based techniques (Ng and Grimsdale, 1996; Gong, Hinds and McCartney, 2001). According to Ng and Grimsdale (1996), energy-based models produce static simulation while the forced-based models produce dynamic simulation or animations. Fabric models developed in the last two decades are characterised by their algorithms, nature of complexity and the computational times required. In-depth analysis of the algorithms is beyond the scope of this discussion. The static and dynamic models notable for the development of 3D CAD clothing systems are highlighted here.

Stylios, Wan and Powell (1996) presented a virtual fashion show by modelling the dynamic drape of garments on virtual mannequins. They joined the 2D garment patterns together virtually over a virtual female body to form the complete 3D garment surface. They simulated two lightweight fabrics made from a cotton/polyester blend and 100% polyester respectively, as materials for the garments.

Volino et al. (1996) described a system for cloth simulation and demonstrated the animation of dressed synthetic characters. The garment simulation software “MIRACloth”, developed at MiraLab (Switzerland), offers the design of 2D patterns, interactive 3D pattern placement on virtual bodies, 3D garment construction, cloth simulation and animation (Volino and Thalmann, 2000). A further development from MiraLab is an efficient tool for dynamic simulation and animation of virtual dressed humans, and it may be used to produce a virtual fashion show (Cordier and Thalmann, 2002; Volino, Cordier and Thalmann, 2005; and Thalmann and Volino, 2005). This modeller is integrated into the virtual garment design and prototyping software “Fashionizer” which significantly advanced the techniques used for virtual fashion shows (Thalmann and Volino, 2005).

Kang and Kim (2000b, 2000c) also demonstrated a clothing design system which had a module for drafting 2D flat patterns, a resizable virtual mannequin and a module for wrapping 2D patterns onto a 3D body. Vassilev (2000) introduced a fast simulation model for dressing a virtual mannequin acquired by 3D body scanning. In addition to the wrapping of 2D garment panels on 3D body models, Chiricota (2001, 2003) showed the automatic modelling of secondary garment parts like collars, waist bands and pockets. Fuhrmann et al. (2003) described a method for interaction-free fully automated dressing of virtual clothing patterns on to virtual models derived from 3D scan data.

Their system was claimed to be the first to allow fully automated and also very fast simulation of clothing on virtual figures

The “2D to 3D” approach to 3D clothing design has been successfully adopted in a significant number of clothing CAD systems that are available on the market.

2.1.3 2D-Sketch-based 3D Simulation

The 2D-sketch-based 3D simulation approach is another version of the “2D to “3D” design approach which works on a 2D sketch or design from the designers instead of 2D patterns pieces. The concept of utilising initial sketch from a clothing or fashion designer to generate virtual clothing is presented by Ito et al. (1992). They postulate a design system that would take an initial design sketch of clothing as its input and would intelligently deliver a set of 2D patterns and a virtual presentation of the 3D garment as its output. Decaudin et al. (2006) and Turquin et al. (2004, 2007) presented a design system that could directly convert an initial 2D sketch into a 3D object without the necessity of any 2D patterns. Their CAD system allowed the designer to sketch garment contours onto a 2D view of a mannequin as shown in Figure 2-9 and could generate 3D virtual garments from the 2D sketch. They (Decaudin et al., 2006) also demonstrated flattening of 2D pattern from a 3D design.

Figure 2-9 From 2D Sketch to 3D Virtual Garment (Decaudin et al., 2006)

2.1.4 Reactive 2D/3D Design Process

Luo and Yuen (2005) presented a 3D system, which followed the "2D to 3D" design approach but which allowed the designer to modify the 2D pattern interactively. The interesting feature of their CAD system is that any interactive change in the 2D pattern pieces could make an automatic change in the corresponding 3D design as shown in Figure 2-10. They termed the process as "reactive 2D/3D garment pattern design".

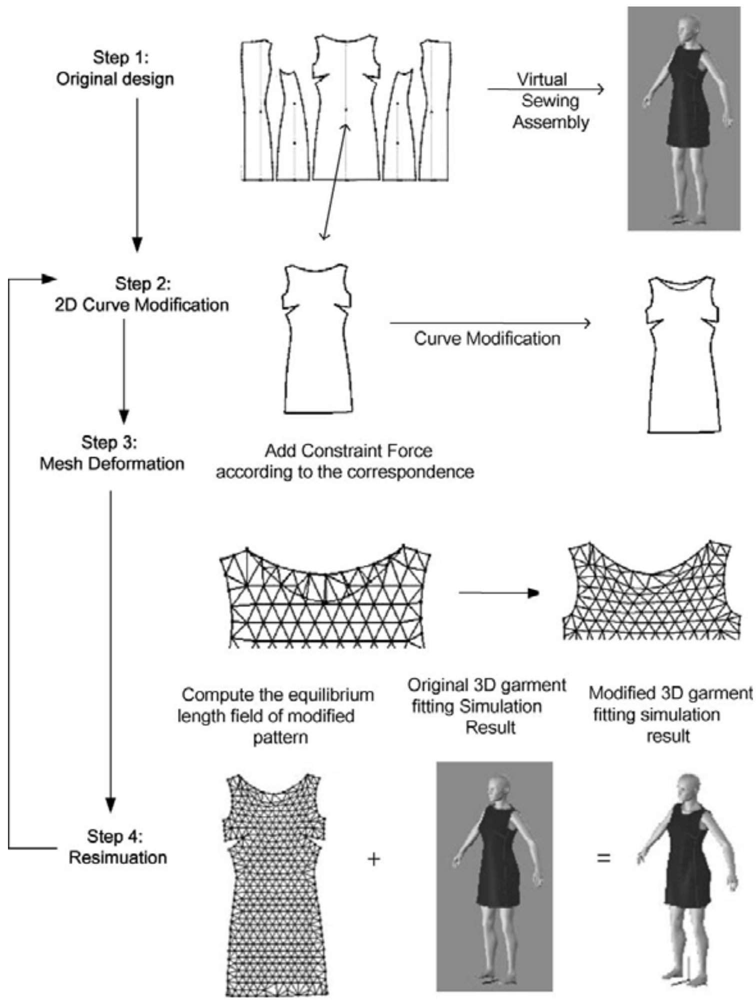


Figure 2-10 Reactive 2D/3D Design Process presented by Luo and Yuen (2005)

2.1.5 Digital Draping

Digital draping is the computerised version of physical draping, the "haute couture" process of pattern creation. It considers fabric as virtual rectangular sheet and drapes it onto a virtual body. The CAD system presented by Sul and Kang (2006) has this characteristic feature. Their system offers virtual pinning and scissoring tools that allow the designer to fix virtual cloth on the mannequin and to remove the redundant cloth parts while digitally draping it onto the mannequin. Their system does not include any flattening module but it can copy the virtual scissoring steps simultaneously in 2D to produce 2D flat pattern pieces.

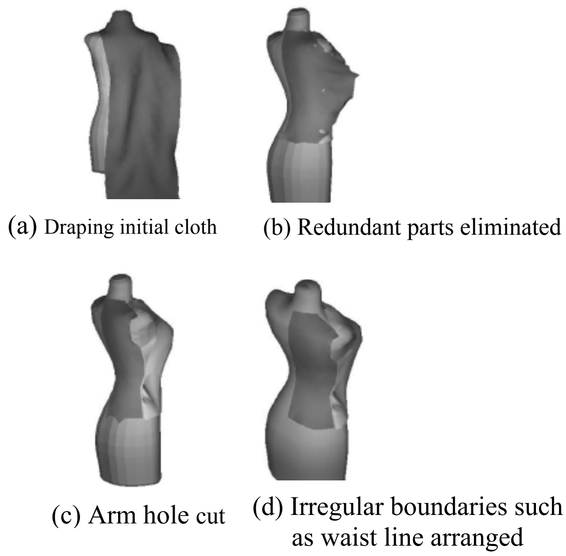


Figure 2-11 Draping Digital Fabric on Virtual Mannequin (Sul and Kang, 2006)

2.1.6 Combined Techniques

There are examples of combining both "2D to 3D" and "3D to 2D" approaches in a single CAD system to extract the benefit of both. Okabe et al. (1992) gave an outline of such a CAD system. Initially written in the programming language of FORTRAN together with application programming interfaces in CORE for 3D viewing and PLOT10 for 2D views, their CAD system was later transferred to a C++ platform with application programming interfaces PHIGS and IDES for both 3D and 2D views to improve the efficiency. They claimed it as the first CAD system that could wrap 2D pattern shapes on to 3D body models, produce drape simulation based on the mechanical properties of fabrics measured by the Kawabata Evaluation System (KES) and also supported direct development of 3D designs on a virtual body to generate 2D pattern pieces. An energy-based modeller for static cloth simulation was incorporated into their 3D CAD. This modeller could accept the mechanical properties of fabrics measured by KES. Okabe et al. (1992) envisaged that their CAD system would be positioned at the centre of a textile information network so that the textile design and clothing design could be processed synchronously and in parallel.

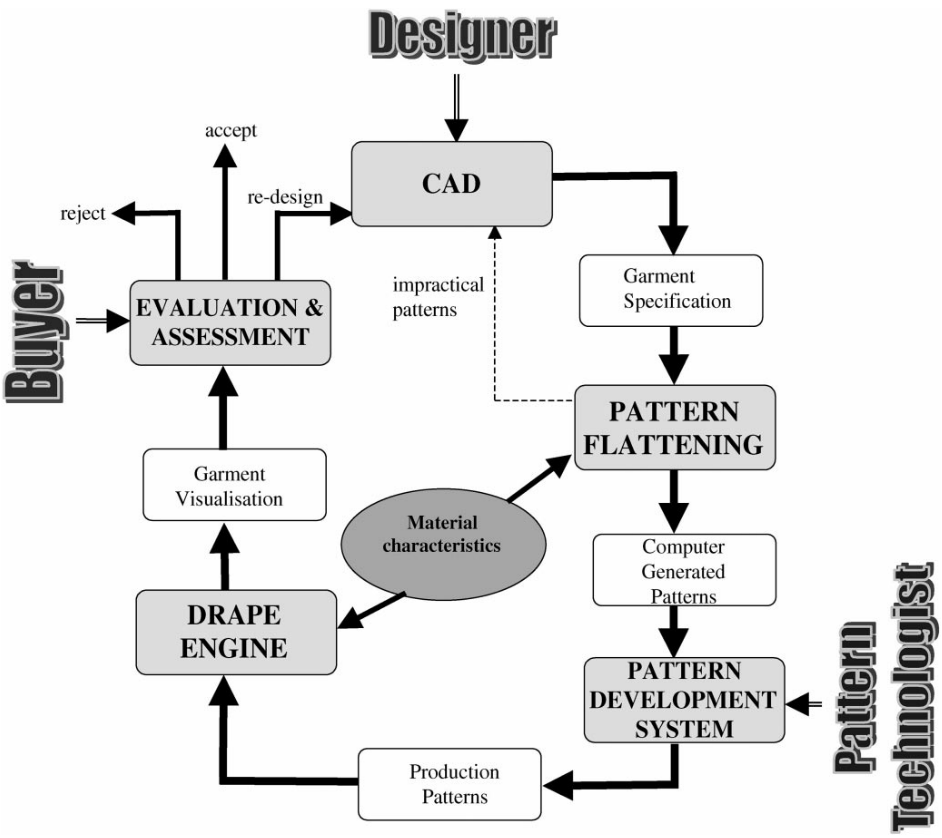


Figure 2-12 Garment Design Model proposed by McCartney et al. (2000)

The garment design model proposed by McCartney et al. (2000) combined "3D to 2D" and "2D to 3D" approaches as can be seen in Figure 2-12. They developed a design system, based on their proposed design process, which had three key components: a design interface for facilitating the creation of 3D garments specifications by the designer, a module for pattern flattening and a drape engine for simulation of cloth materials in 3D. As already described in section 2.1.1, they demonstrated designing of a garment panel on a virtual mannequin, its drape simulation and flattening into 2D. Although their system is mainly effective for close-fitting garments, their garment design model provides a solution for virtual fit checking and a reduction in dependency on physical prototyping.

The CAD system presented by Fontana, Rizzi and Cuguni (2005) included a 3D modeller, a 2D CAD unit and a 3D simulator. The design process using their CAD system is represented in Figure 2-13. The 3D modeller could facilitate the modification of garment design from a range of available 3D designs. The 2D CAD unit could generate 2D pattern pieces from 3D designs and the 3D simulation unit could replicate the fabric behaviour and drape to allow the designer to review and evaluate the fit and appearance of the garments.

Figure 2-13 3D Design Process followed in the CAD System of Fontana, Rizzi and Cuguni (2005)

Fang and Ding (2008) proposed a 3D clothing design process which also covers both the “3D to 2D” and “2D to 3D” approaches (see Figure 2-14). Their design process includes the use of a digital human body as a platform for 3D garment design, automatic flattening of patterns and the use of flat pattern virtual fit simulation in conjunction with an interactive fashion show. They also demonstrated the 3D design of upper body garments on a virtual mannequin made from body scan data.

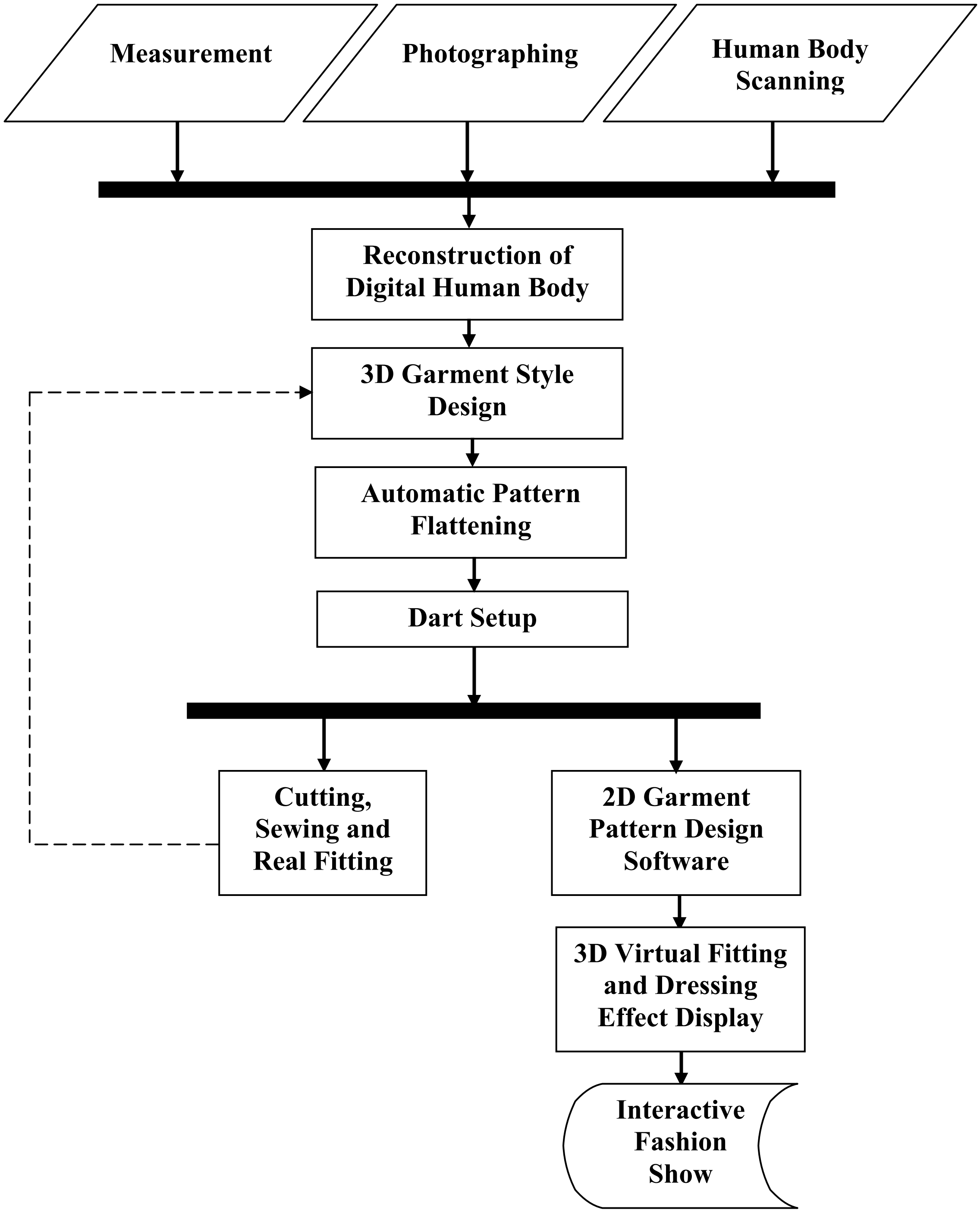


Figure 2-14 3D Garment Design Process proposed by Fang and Ding (2008)

2.2 Virtual Mannequins as Design Templates

Virtual mannequins serve as the design platform upon which to develop 3D clothing design in a CAD system. Evidence of work on developing virtual human models goes back to the late 1950s and early 1960s but the early models were not built to target the clothing industry, rather for ergonomic analysis targeting the aeroplane and automobile industries (Thalmann and Thalmann, 2004). The use of virtual human models for clothing design was seen at the beginning of the 1990s in the work of Hinds and McCartney (1990). Initially no realistic human model was used; rather virtual forms of dress dummies were used in the 3D CAD systems (Hinds and J. McCartney, 1990 and Okabe et al., 1992).

The major techniques that are used for virtual human modelling can be categorised as creative, reconstructive and interpolated (Mao, Qin and Wright, 2009). The creative techniques utilise 3D drawing and rendering facilities available within 3D CAD software packages (e.g. 3D Studio Max®, Maya) to develop human models from first principles. These techniques are commonly used to create cartoon and movie characters, but are not reliable enough to build human models for 3D clothing development as they cannot reproduce the body geometry and anthropometry as realistically as required for this purpose. The techniques that follow the reconstructive approach work on the 3D information of a real human body or dress form captured by devices such as the still camera (Wang et al., 2003 and Lee, Gu and Thalmann, 2000), video camera (Plankers, Fua and D'Apuzzo, 1999), sliding gauge (Kang and Kim, 2000b) and 3D body scanner (Kim and Kang, 2002; Seo and Thalmann, 2004 and Cho et al. 2005). Body scanners provide an easy and efficient way of capturing anthropometric information to construct a realistic virtual human model with a CAD system (Jones et al., 1995). This approach can reproduce the anthropometry and body geometry realistically. Naturally these techniques are well suited for creating virtual models for clothing CAD systems. The interpolated technique is used for creating size and shape modifiable body models (Seo, 2004 and Seo and Thalmann, 2004). This approach uses a range of scanned examples and stores their size and shape information in its database to generate new bodies through interpolating existing information.

Both non-resizable and resizable body models are used in clothing CAD systems. Non-resizable ones can be used only for one size of cloth; so several standard sized models should be required in a CAD system to cover a range of sizes. The resizable mannequins are more beneficial and user-friendly from a designer's point of view. Kang and Kim (2000c) introduced a resizable body model to handle the mass production of different sized garments. They developed an algorithm that could generate different sizes of body models from a standard body model using statistical calculation. Initially they used the anthropometric sliding gauge to capture the anthropometric data as mentioned already. In their later work (Kim and Kang, 2002) they scanned the human body to capture point clouds for generating virtual models to be used as a platform for 3D garment design.

Seo and Thalmann (2004) showed the techniques for generating realistic and parametric human models from body-scan data and modifying them according to the size parameters. They considered eight anthropometric measurements (five girths and three lengths) as essential size parameters. Girth measurements which they considered were neck, chest/bust, under-bust, waist and hip and the lengths were height, arm length and crotch length. By changing the size parameters, their modelling synthesiser could output differently sized and shaped models as seen in Figure 2-15. Their modelling synthesiser could also impart dynamic movement to the virtual model to produce animated characters.

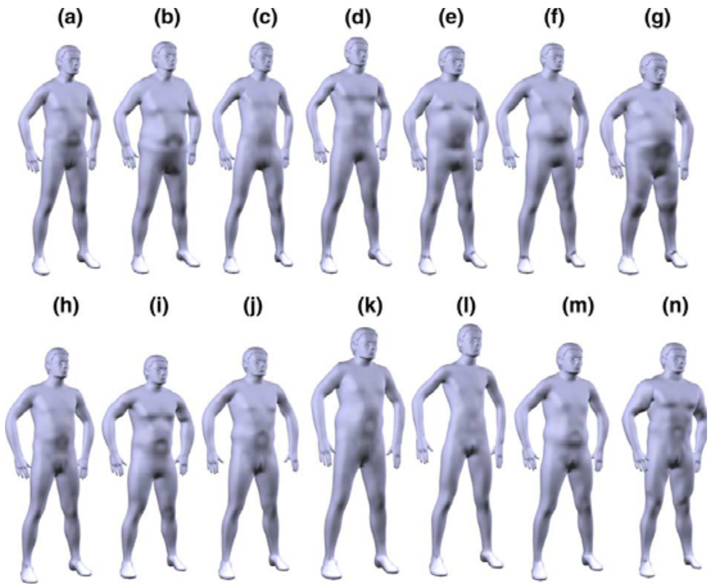


Figure 2-15 Differently Sized and Shaped Body Models generated by the Synthesiser of Seo and Thalmann (2004)

Another process for developing a parametric human model using available 3D CAD software was presented by Sayem (2004). The process used an available virtual model resulting from body-scanned data as a basis for developing a parametric model from it. The model was specified using 19 parameters which comprise 16 closed-curve measurements and 3 additional breast parameters such as breast height, distance between breast points, and breast diameter. The developed parametric model was used for 3D design of close-fitting garments and also for 3D grading, just by incorporating the appropriate size tables. It is reported that the anatomical landmarks presented in traditional size tables are not adequate for accurately reproducing a realistic human model from parameterised curves.

Cho et al. (2005) developed an interactive body model system which included a female virtual mannequin made from 3D body scan data and which offered eight slide bars for controlling shape parameters and three slide bars for controlling length (see Figure 2-16). Using the slide bars the user can change the size and shape of the mannequin which can be used for pattern making. Later they (Cho et al., 2006) also demonstrated a posture and depth adjustable body model for use in the clothing industry.

The software package 3D Modaris Fit from Lectra (France) contains such adjustable mannequins which can be resized using slide bars.

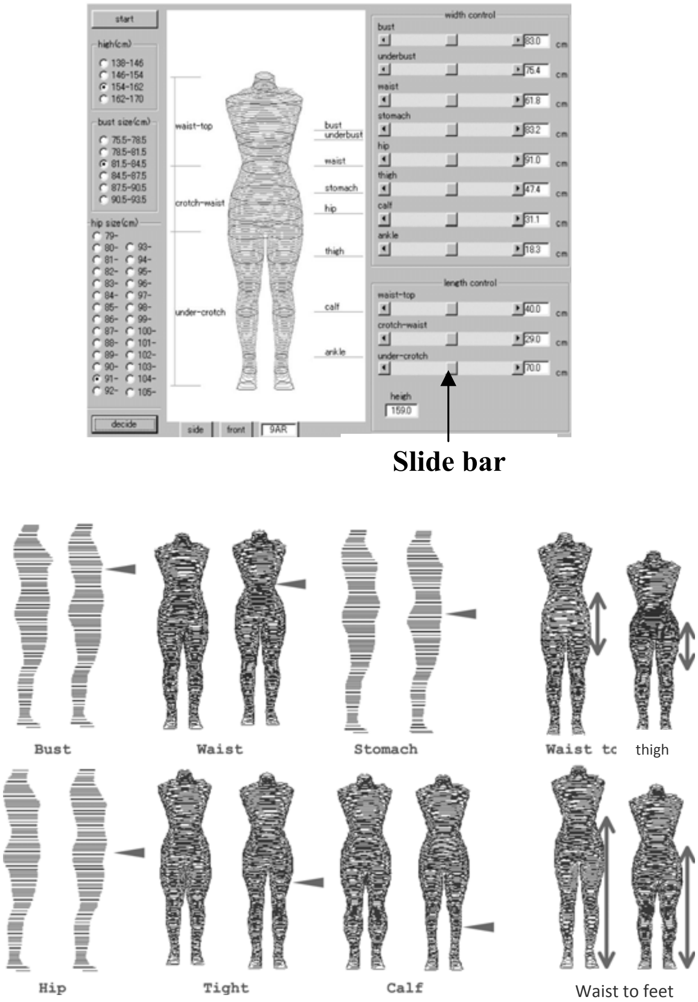


Figure 2-16 Interactive Body Model System by Cho et al. (2005)

2.3 Available 3D Clothing CAD systems

Based on their working procedure to create 3D designs, commercially available 3D clothing CAD systems can be divided into the following three groups.

- 3D Interactive System;
- 2D-to-3D Simulation System;
- 3D-to-2D Unwrapping System;

3D interactive systems, which include software such as *Virtualfashion®* from Reyes Infografica (Spain) and *Automatic Pattern Generation System (APGS)* from TPC (HK) Limited (Hong Kong), allow the designer to develop garment silhouettes and styles in a 3D environment according to their preference.

A 2D-to-3D simulation system allows the importation of 2D pattern pieces from the appropriate 2D CAD software to wrap them onto a virtual model to visualise the virtual product and also to simulate fabric drape and fit as already mentioned in section 2.1.2. This group includes *Vstitcher*™ from Browzwear (Israel), *Accumark Vstistcher*™ from Gerber (USA), *Haute Couture 3D* from PAD system Technologies Inc. (Canada), *Modaris 3D FIT* from Lectra (France), *efit Simulator*™ from Tukatech (USA), *3D Runway* from OptiTex International (Israel) and *Vidya* from Assyst (Germany).

3D-to-2D unwrapping systems include the software packages: *3D Interactive software* from TPC (HK) Limited (Hong Kong) and the flattening tool of *3D Runway* from OptiTex International (Israel). These two software packages provide the capability to execute pattern unwrapping in a very limited context and only for close-fitting garments. The software *DesignConcept* from Lectra (France) is capable of executing 3D to 2D pattern unwrapping, but is currently being promoted for use in car seat design and for technical textiles applications. It has been used experimentally for creating 3D virtual designs of close-fitting garments after customising it with additional components (Sayem, 2004 and Roedel, 2008).

These software packages are reviewed in this section. The major features of the available 3D systems are summarised in Table 2-1.

Table 2-1 Available 3D Clothing CAD Systems [Derived from Sayem, Kennon and Clarke (2010)]

Software / Features	Virtualfashion®	Modaris 3D Fit	Vstitcher™	Haute Couture 3D	eFit Simulator™	Vidya	3D Runway	TPC APCS/PPG	TPC 3D Interactive	DesignConcept
Wrapping 2D patterns on 3D body	-	√	√	√	√	√	√	-	-	-
Developing 3D design on 3D body	√	-	-	-	-	-	√	√	√	√
*Flattening 2D patterns from 3D design	-	-	-	-	-	-	√	-	√	√
Realistic fabric draping	√	√	√	√	√	√	√	-	-	-
Adjustable mannequin	-	√	√	-	√	√	√	-	-	-
Dynamic pose/ virtual fashion show	**√	-	-	√	√	√	√	-	-	-

**for close-fitting garments only, **when used together with the software "VFshow".*

2.3.1 Virtualfashion®

Virtualfashion® has two available versions: *VF Professional* and *VF basic*. It contains 3D garment moulds linked with virtual human models for use as a 3D design platform, as can be seen in Figure 2-17, and it provides a 3D workspace for the designer to create 3D designs interactively. According to the user manual of VF Professional 1.5 (n.d.), there are built-in male and female virtual models within the software for design purposes. It also allows the designer to import models from Poser and Daz, which are specialised software packages for creating 3D characters. Using this software, the designer can interactively change features such as posture, facial gesture, hair style and colour and as well as the skin colour of the models. In order to develop 3D clothing designs, the software allows the designer to select any of the available garment moulds associated with either a male or female model and to start modifying it using the available cutting tools as can be seen in Figure 2-17. Once the modification is finished, the designer can apply fabric to the design from a fabric library. However the software does not have a very large collection of fabrics in its library. A limited selection of fabrics ranging from heavy cotton to silk, wool and denim is possible. It only offers tools to change the brightness, colour and opacity of the fabrics available in its library. The software has a physics-based drape module to simulate fabric behaviour but it does not accept any input of fabric properties to create new fabrics according to the designer's choice. This marks the limitation of the software package. This software can work seamlessly with another program "*VF show*" from the same supplier to produce animation of dressed models or a virtual fashion show. It is a useful software package for fashion drawing, product line creation, line selection and visual communication, although it can neither make any use of 2D patterns nor output any.

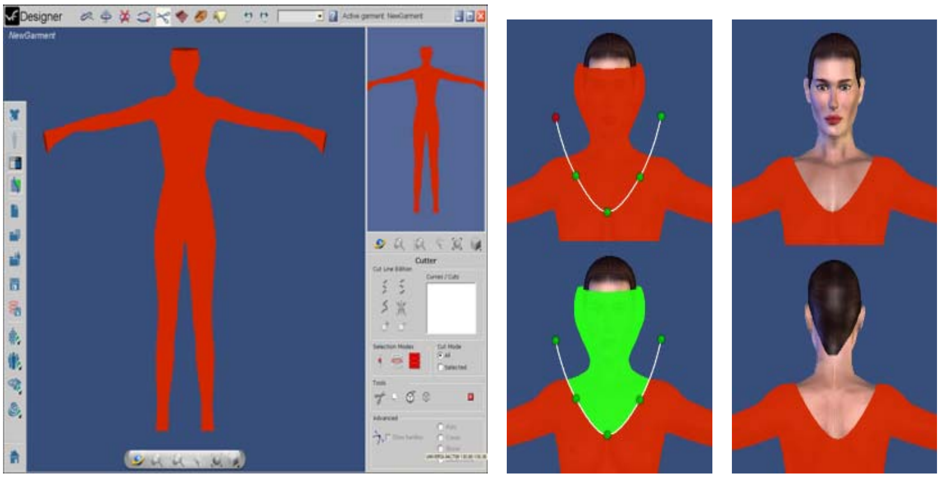


Figure 2-17 3D Design Process by modifying a Garment Mould in *Virtualfashion*® (Source: VF Professional 1.5 User Reference)

2.3.2 Automatic Pattern Generation System (APGS)

According to TPC (n.d.), APGS is an integrated 3D solution that considers garment fit and size grading. It has three components: a parametric human generator (PHG), a parametric pattern generator (PPG) and a parametric pattern accelerator (PPA). The PHG module includes tools to create a virtual mannequin from body scan data. PPG facilitates garment designing on mannequin with pre-defined garment structures and representing the volume and silhouette of the garment structure in 3D space. Designers can evaluate the garment volume and silhouette in 3D and modify it as necessary. Its 2D PPA module can generate 2D patterns simultaneously based on the designer's adjustment and modifications to the 3D design and it facilitates printing or plotting of flat pattern pieces.

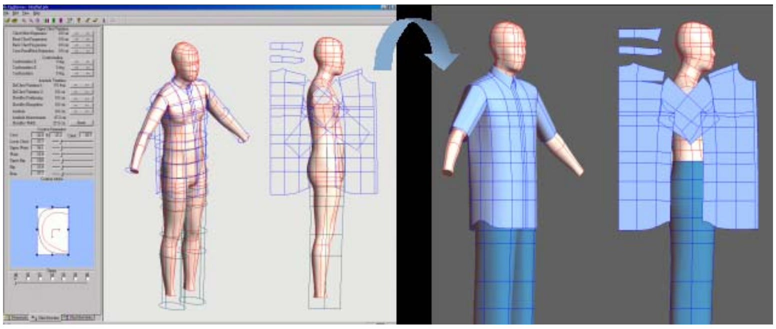


Figure 2-18 3D Garment Design by PPG (TPC, n.d.)

2.3.3 Vstitcher™ and Accumark Vstitcher™

VStitcher™ is 3D garment visualisation and drape simulation software from Browzwear (Israel). Gerber (USA) has merged this software with its pattern design, grading and marker making software *AccuMark* and now it offers to the market as *AccuMark VStitcher™*. *VStitcher™* has the capability of producing virtual prototypes from 2D pattern pieces, directly assembling them on a real size virtual mannequin. According to Browzwear (n.d.), the software comes with a set of built-in and integrated virtual mannequins which can be customised by means of a range of parameters such as body measurement, posture, skin tone, hair style and also the stages of pregnancy where appropriate. The drape module of the software can reproduce the fabric behaviour realistically, based on physical characteristics. The software includes features of a 2D/3D reactive design process similar to that of Luo and Yuen (2005). When a designer needs to modify any part of a pattern pieces, 3D simulation of that pattern pieces can automatically adopt that particular change. This gives the opportunity of conducting a fitting trial and finalising the production pattern without any physical prototype. The available texture-mapping tools within the software allow the application of any print design, stitches, prints and any motifs on the 3D design. Another useful feature of this software package is its ability to support the real-time fit approval sessions online across the globe on an internet platform.

2.3.4 Haute Couture 3D

Haute Couture 3D (HC3D) is garment visualisation software which utilises 2D pattern pieces to generate 3D garment simulation. According to PAD System (n.d.), the cloth simulation tool Syflex™ is seamlessly integrated into it. It can apply colour, textures and prints on 3D design through its texture mapping tools to produce a realistic virtual prototype for the facilitation of fit evaluation and line selection. It allows the designers to customise the fabric properties by inputting measured results from fabric evaluation systems in order to view the differential drape output. It is reported that this software is compatible with 3D graphic software Maya™ and other 3D animation applications. It can also be used to create animated dressed characters for the animation and film industries.

2.3.5 Modaris 3D Fit

Modaris 3D Fit is a 3D virtual prototyping solution from the French software company Lectra. It associates 2D patterns, fabric information and 3D virtual models to produce virtual clothing. Its latest version (Modaris V7-3D) has a library of standard and configurable men's, ladies' and children's (both boys and girls) mannequins and a broad database of 150 commonly-used materials together with their mechanical characteristics. When integrated with Lectra's 2D pattern making solution "Modaris", it can simulate the 3D design of any clothing items from their 2D pattern pieces developed by any 2D CAD software suite. This software makes virtual try-on possible and allows an on-site or remote review of the virtual prototypes. Garment fit can be checked in various fabrics and sizes. Using the new fabrics creation tool, the designer can create his own fabric by inputting fabric properties into the system in order to view the differential drape. According to Lectra's website, a company can reduce development costs and times by limiting the number of physical prototypes necessary by using this software (Lectra, n.d.).

2.3.6 eFit Simulator™

The *eFit Simulator*™, currently renamed as TUKA3D™, is another "2D-to-3D" simulation software suite that accepts 2D pattern pieces drafted separately to produce digital garment prototypes. It exploits advanced cloth simulation technology to reproduce realistic drape and fabric nature, taking fabric properties into account. Similarly to other software packages of its type, it also comes with a set of virtual fit models. In addition to the draping of 2D patterns on virtual models, it can generate animation and a virtual catwalk of dressed models to facilitate evaluation of fit and style. It has a physical tension-mapping tool to evaluate the looseness and tightness of virtual clothing on the mannequin. It supports online 'virtual fit sessions' across the world among the partners using the same systems and facilities to make dynamic storyboards for presentation purposes. According to a press release from Tukatech (n.d.), several large clothing retailing companies including the companies Maggy London, Tesco, Phillip Van Heusen and Jones New York Intimates are using this virtual prototyping solution.

2.3.7 Vidya

Vidya is a German development of 3D draping software which can be used in the clothing industry for product-development and virtual fashion shows, and also in the games and film industry for making animated characters (Assyst-bullmer, n.d.). It offers complete integration with body scanning technology to develop customised virtual mannequins. It also offers a set of ready-made but customisable mannequins which are flexible in respect of size and shape changes according to the designer's choice. It works on the basis of a "2D to 3D" design principle. Flat patterns pieces drafted in a 2D CAD system can easily be linked with *Vidya* to three-dimensionally position them on a selected mannequin for producing a virtual garment. The integrated drape engine can impart material realistic simulation of drape behaviour on the virtual garment. To make the 3D design even more realistic, it can add seams, buttons, appliqués, seam lines, linings and folds as imagined by the designer. Fabric checks, stripe, print and colour can also be reproduced using the texture mapping tools. It has a wide range of built-in fabric data base available for designer's selection during the garment simulation and visualisation processes. Furthermore it accepts the results from fabric testers such as the Drape-O-Meter, developed by the Hohenstein Institute, Germany, and from Fabric Assurance by Simple Testing (FAST) developed by CSIRO (Commonwealth Scientific and Industrial Research Organisation) in Australia.

2.3.8 3D Runway

3D Runway is a garment simulation software package which can support both 2D-to-3D simulation and 3D-to-2D unwrapping. It offers a suite of tools known as *3D Runway Designer, 3D Runway Creator* and *3D Flattening*. The first two tools support garment visualisation and 3D draping based on 2D flat patterns. The *3D Flattening* tool of the 3D Runway program offers the opportunity of extracting 2D pattern pieces from 3D designs but is limited to only close-fitting garments, as may be seen in Figure 2-19. The software includes a range of parametric mannequins to be used as 3D design platforms. These mannequins are customisable by means of five adjustable body measurements and several posture positions. The available texture mapping tool helps to visualise any design details in the form virtual clothing. According to OptiTex (n.d.), this software can help its user to reduce the time-to-market and to minimise material waste in the product development phase.

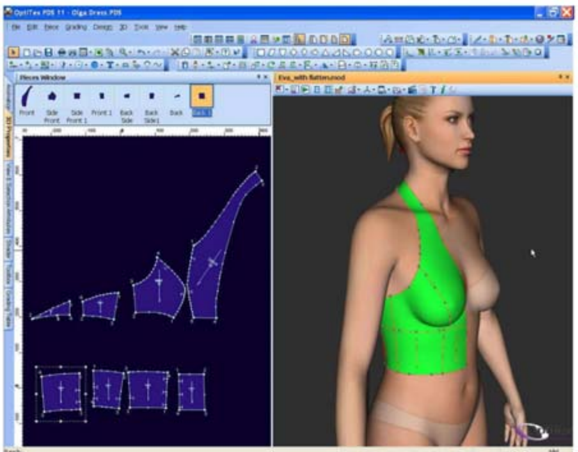
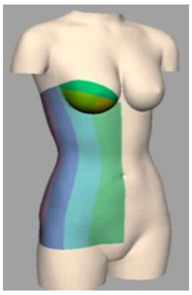


Figure 2-19 Examples of 2D Patterns (Left) Extracted from 3D Designs by the 3D Runway Flattening Tool (OptiTex, n.d.)

2.3.9 3D Interactive Software

3D Interactive software is another 3D software product from TPC (HK) Limited (Hong Kong). It offers a 3D working environment for pattern designers. It exploits 3D relational-geometry to convert 3D designs developed on a virtual mannequin automatically into 2D master slopers. However it offers solutions only for close-fitting garments.



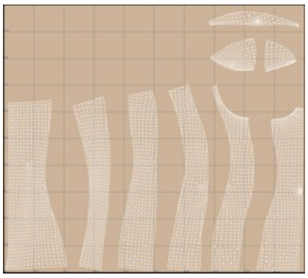


Figure 2-20 Examples of 2D Patterns (Right) from 3D Design using the *3D Interactive software* from TPC (HK) Limited.

2.3.10 DesignConcept

DesignConcept from Lectra (France) is a combined 2D and 3D software solution. It is built on Topsolid, which is a software package for 3D mechanical design from another French company, Missler. The software DesignConcept has two versions available on the market; DesignConcept Auto and DesignConcept TechTex, which are currently being offered for the automobile and composite industries respectively. Its capability of producing 2D templates from 3D designs using the flattening mechanism is a remarkable feature of this software. This gives the opportunity to execute “3D to 2D pattern unwrapping” for clothing product-development purposes. But this software does not come with any design platform for developing clothing product. It has been used experimentally for the development of parametric virtual models to create 3D designs of close-fitting garments and for the extraction of 2D pattern pieces (Sayem, 2004; Roedel, 2008).

2.4 Advantages of 3D Clothing Design

3D clothing design systems offer a number of benefits over 2D clothing design systems in use. Virtual prototyping using computer-based 3D clothing product-development techniques results in fewer physical prototypes and a shorter product-development phase (Ernst, 2009). For decision-making on product selection and prior to the commencement of production, it is usual for at least two up to ten physical prototypes to be made when using existing traditional product-development systems (Lectra Bylined Article, n.d.). Gray (1998) mentioned that more than seven out of ten samples (prototypes) could be rejected through rigorous assessment by retail buyers in the United Kingdom (UK). This incurs a high cost involvement and time consumption. According to Lectra (n.d.), Browzwear (n.d.) and Tukatech (n.d.); virtual prototyping and virtual try-on processes can significantly reduce the product-development time and cost. Virtual review and evaluation of fit with realistically simulated fabric behaviour can enable faster detection of errors and earlier corrections to design elements, material selection and assembly. At the same time, the virtual prototypes can be used as a marketing aid for online product presentation and internet-based retailing.

The application of flattening technology provides the opportunity to combine clothing design and pattern creation in to a single step. Successful implementation of 3D to 2D unwrapping technology in the clothing industry may make an important contribution to the product-development phase. Automatic flat pattern extraction from 3D designs offers a considerable reduction of the time and manpower involvement in the pattern cutting process.

3D clothing design systems may also smooth and accelerate the flow of design information across the textile and fashion industry. According to Okabe et al. (1992), a 3D CAD system will form the nerve centre of at the centre of a textile information network as may be seen in Figure 2-21.

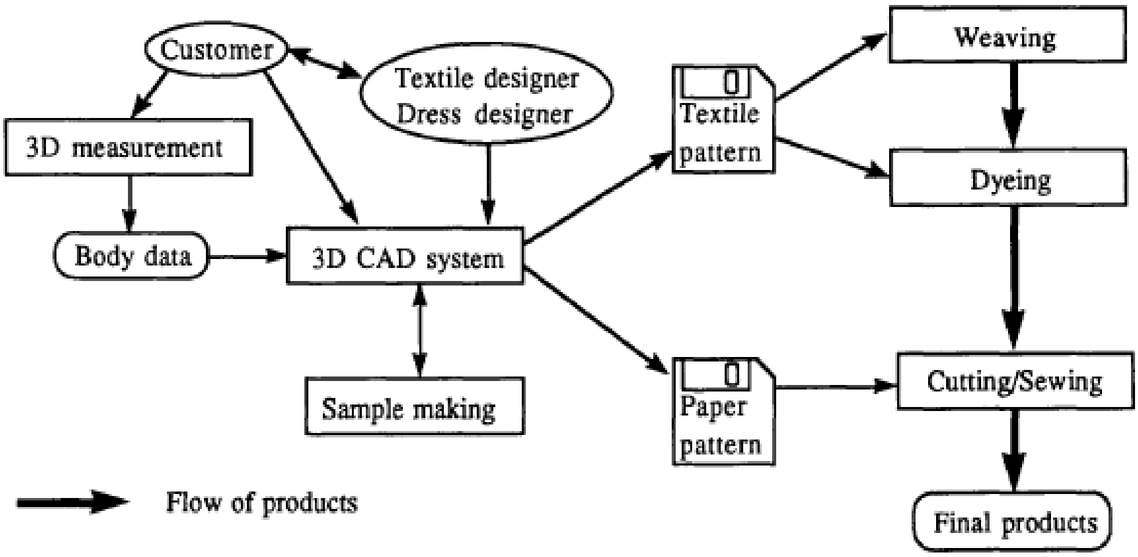


Figure 2-21 Position of 3D CAD System in a Textile Information Network (Okabe et al., 1992)

2.5 Modern Anthropometry

Anthropometry, the science of human body measurement, forms an indispensable part of industrial design, clothing design, ergonomics and architecture. Traditionally the human body is measured manually using instruments such as an anthropometer, callipers, a sliding compass and measurement tape (Roebuck, Kroemer and Thomson, 1975 and BS EN 13402-1, 2001). During a manual measurement, it is necessary to define the position of measurement points or "landmarks" with the help of anatomy, a branch of medical science (BS EN 13402-1, 2001 and Simmons and Istook, 2003). For example, according to the British standard and European Norm BS EN 13402-1 (2001) the waist girth has to be measured at the natural waist line lying between the top of the hip bone (iliac crest) and the lowest rib bone. Identifying the landmarks according to anatomy is not an easy task for all. It is also time-consuming. An anthropometric survey done in the US Army in 1988 required four hours for identifying the landmarks, taking measurements, and recording measured data for each subject (Paquette, 1996).

Modern anthropometry incorporates the use of 3D non-contact body-scanning systems. Today it is possible to collect anthropometric data at very high precision without touching the human body, with the help of scanning technology. Other than the uses in anthropometry and clothing virtual fit analysis, 3D body-scanning systems are also in use in a variety of areas such as statistical analysis, modelling, animation and medical science.

2.5.1 3D Body-scanning Systems

It has been reported by Simmons and Istook (2003) that several devices for scanning only one side of body at a time were developed in the twenty years between 1964 and 1984. A system capable of scanning the human body from all sides surrounding the body using a horizontal sheet of light was described in 1985 (Magnant, 1985). Currently several Asian, European and American companies are producing fast and efficient 3D body-scanners (Yu, 2004). The common components of a body-scanning system include one or more light or different wave sources; vision or capturing devices; software; a computer system; and a display unit (Istook, 2008). Based on the reflection medium used, the available body-scanning systems can be categorised into two groups: the optical systems and radio- or microwave systems, where the optical systems can be either white light-based or laser-based (Istook, 2008). Table 2-2 provides a list of the major body-scanning systems available on the market.

Table 2-2 Major Body-scanning Systems

Body-scanning Systems		
Optical systems		***Radio- or micro wave systems***
Light-based systems *Examples:* - SYMCAD™ ST, (Telmat, France)[1] - NX16, LC16 ([TC][2], USA)[2] - Triform (Wicks and Wilson, UK)[3] - BodyScan 3D (Breuckmann, Germany)[4]	**Laser-based systems** *Examples:* - Body line (Hamamatsu, Japan)[5] - WBX (Cyberware, USA)[6] - Vitus smart LC, Vitus smart XXL (Human Soutions, Germany and Vitronic, Germany)[7] - LPW-1100, LPW-2000FW, HEW-1800 (Voxelan/Hamano, Japan)[8]	*Example:* - Intellifit Virtual Fitting Room™ (Intellifit, USA)[9,10]

Sources: [1]Symcad (n.d.), [2]TC2 (n.d.), [3]Triform (n.d.), [4]Breuckmann (n.d.), [5]Hamamatsu (n.d.), [6]Cyberware (n.d.), [7]Human Solutions (n.d.), [8]Voxelan (n.d.), [9]Intellifit (n.d.), [10]Istook (2008)

2.5.2 Benefits and Limitations of 3D Body-scanning

3D body-scanning offers manifold advantages over the traditional anthropometric methods. Current body-scanning systems can capture the size and shape of a human body within a very short period of time. The measured data can be stored in the computer system and can also be retrieved at any time. Automatic extraction of size information from the scanned data is possible using relevant software. The accuracy of scan data is very high as the inter- and intra-personal errors which arise during manual measurements can be avoided.

It is possible to build realistic 3D virtual human models easily and efficiently from the body-scanned data, as already mentioned in section 2.2. This leads the way towards virtual prototyping through 3D garment design and 3D grading techniques.

Unlike conventional pattern creation, 3D garment design on a virtual model requires no use of any size specification in the design process. Size specifications are required only to create or resize the virtual models which work as drawing platforms for the clothing designers. Traditional anthropometry is not enough in all cases to derive the size specifications required to develop a virtual model. Specifically measurements such as breast height and breast diameter can easily be extracted from 3D scanned data, as can be seen in Figure 2-22 (Kirchdörfer and Rupp, 2007). A significant advantage of using body-scanning technology is that it simplifies the measurement of elderly people and taking measurements for which there are no reliable landmarks.

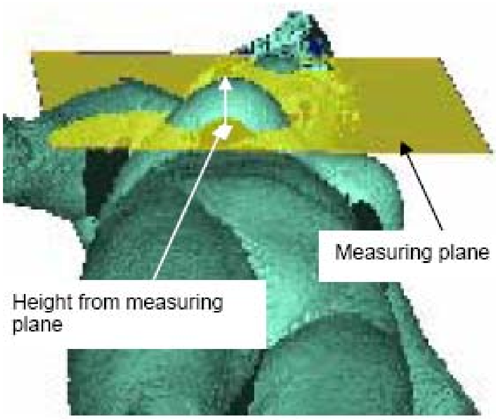


Figure 2-22 Measuring Breast Height on a Virtual Model (Kirchdörfer and Rupp, 2007)

Together with the benefits and potential, there are also some limitations with the current body-scanning systems which demand more research and development. Some of the limitations are related to the reflection media used (white light, laser or radio/micro-wave) and image capturing techniques (Istook, 2008).

Almost all scanners are unable to record the image of some body parts which remain hidden in standard standing postures regardless of which technology is used. Re-entrant and concave curves such as the armpits, the crotch and the areas under the bust and chin cannot be captured properly either by laser-based or light-based scanners as shown in

Figure 2-23 (Kirchdörfer and Rupp, 2007; Daanen and Jereon-van-de-Water, 1998). Areas of uncertainty arise due to missing data in these particular areas and need to be synthesised with the help of software functions either automatically or interactively.

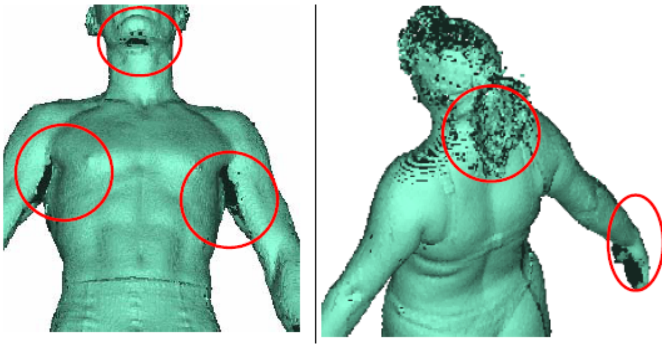


Figure 2-23 Shaded Areas due to Missing Data during Body-Scanning (Kirchdörfer and Rupp, 2007)

Very small body parts such as fingers and toes and body parts covered by hair also present problems that the various scanner technologies struggle to capture (Kirchdörfer and Rupp, 2007). Long hair can also obstruct the identification of landmarks around the neck and shoulders during the extraction of size data from the scanned body image, which is particularly important while scanning a female subject (Istook, 2008). Skin and hair colour play a significant role on the even reflection of light in the light-based scanning system and can affect the quality of the captured image (Istook, 2008).

For both the white light and laser-based systems, the person to be scanned is recommend to wear close-fitting but not constricting garments, as the scanners capture the cloth surface and the skin surface due to the reflection of the light from them. This requires the person being scanned to be undressed to a certain extent which might not be acceptable for all, particularly for women in Muslim societies. It is reported that only radio-wave-based technology, for example the scanner from Intellifit, is capable of measuring a clothed person, as the low frequency radio waves can pass through the textile materials and get reflected off the human skin (Istook, 2008 and Intellifit, n.d.).

It is reported that respiration and foot position of the person to be scanned can significantly affect the body-scanned data and can introduce errors (Mckinnon and Istook, 2002).

For high performance clothing like sportswear, it would also be necessary to consider the dynamic body posture also; however, the 3D scanning technology is still not capable of capturing this accurately as reported by Chi and Kennon (2006). They suggested further development of both hardware and software for 3D scanning systems in this regard.

One important aspect of scanned body measurement which brings into question the compatibility of measurements extracted from the scanned data is the absence of any global standard for landmark identification by body-scanning systems. As a result, different definitions of landmarks prevail among the various scanning systems from different suppliers and the measurements resulting from them are not comparable (Simmons and Istook, 2003). This demands the revision of current sizing and body measurement standards in the context of 3D body-scanning or creation of new standards specifically for body-scanning systems.

2.5.3 Sizing Surveys using 3D Body-scanning Systems

3D body scanners are already in widespread use for sizing surveys around the world. The Japanese size survey (1992-1994), the Civilian American and European Surface Anthropometry Resources (CAESAR) (1998-2002), the Netherlands survey Nedscan (2000-2002), Size UK (1999-2002), Size USA (2002-2003), the German Bra and Elderly Women survey (2002), the African body dimensions (2004 - onward), the size survey of Chinese women (2003), Size Korea (2003 -2004), the French survey (2006) and Size Germany (2007 – 2008) used 3D body-scanning systems (Istook, 2008 and Kirchdörfer and Rupp, 2007).

Some of the resulting datasets from these surveys are available for purchase for particular uses as listed in Table 2-3 (Kirchdörfer and Rupp, 2007). These datasets contain 3D models of the persons scanned under the sizing surveys. For example, SizeUK includes 3D models of selected population subsets categorised by age, region, socio-economic group or ethnicity (SizeUK, n.d.). This gives the opportunity of selecting the representative 3D models from each subset to develop parametric virtual models as 3D design platforms for virtual clothing. Also the relevant size database can also be developed from them for the purpose of automatic 3D grading, targeting the mass production of apparel for retail markets.

Table 2-3 Available Datasets from Sizing Surveys (Kirchdörfer and Rupp, 2007)

Dataset	Provider	Available since
German Bra and Elderly Women survey	Hohenstein Institute, Germany, www.hohenstein.de	2002
CAESAR Project	SAE International, USA, www.sae.org	2002
SizeUK	Bodymetrics, UK, www.bodymetrics.com	2004
SizeUSA	[TC^2] , USA, www.tc2.com	2004
French Survey	IFTH, France, www.ifth.org	2006

2.6 Ease in Clothing Design

The gap between a wearer's body and the clothing item being worn is known as 'ease'. Ease can be of two types: functional (wearing) ease and design (styling) ease (Kincade, 2008). Functional ease is incorporated into a pattern to allow for body expansion, for example chest expansion while breathing in and out, and to allow movement of limbs without discomfort to the wearer. The amount of ease allowance to be added to the pattern is dependent on the type of garment, the type of fabric and the gender and the activities of the wearer. Ease can even be negative in certain cases for close-fitting garments if made of stretch fabric containing elastane fibres.

During the design process, a designer gives only a subjective outline of the design ease but does not include the functional ease. The pattern engineer incorporates ease within the pattern with consideration for the designer's concept, the fabric properties and the consumer's requirements. There is no formula except depending on experience and common practice which help determine the amount of ease to be incorporated into pattern pieces (Petrova and Ashdown, 2008; Gill and Chadwick, 2009).

A clinical study by Moll and Wright (1972) revealed that normal chest expansion during breathing varied by age and sex (see Table 2-4). Both for male and female, the mean chest expansion increases with increase of age up to 34 years, but after the age of 35, it follows a decreasing trend with advancing age. The study was intended for medical research, but it provided a clear indication of minimum ease requirements across the chest area. While investigating the effect of respiration on body-scanned data, Mckinnon and Istook (2002) found that circumferential measurements of the chest/bust, neck, and waist varied during inhalation and exhalation. This finding also indicates that clothing should provide sufficient ease for the normal breathing of the wearer. Koblyakova (1980) considered the effect of breathing to derive minimum ease values for comfort of movement in upper-body garments.

Table 2-4 Chest Expansion during Breathing (Moll and Wright, 1972)

Age (Years)	**15-24**		**25-34**		**35-44**		**45-54**		**55-64**		**65-74**		**75+**	
Sex	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**
Mean Expansion (cm)	7.01	5.55	7.37	5.46	6.56	4.57	6	4.82	5.51	3.77	4	3.76	2.81	2.45
Range (cm)	4 - 10	3.6 - 9.5	4.3 - 9.5	3 - 7.6	3.4 - 11.8	2.7 - 7.1	2.7 - 10.7	2.6 - 7.5	1.7 - 9.2	1 - 5.9	2 - 5.7	1.1 - 6.3	2 - 4.1	1.1 - 4.2

Other than breathing, the movement of body parts also results in a change of shape and skin dimensions (Kirk and Ibrahim, 1966; Chi and Kennon, 2006). Chi and Kennon (2006) identified the significant dimensional changes of skin around the armhole during different arm movements, which should be taken into account while incorporating ease into the garment sleeve, especially for functional garments.

In addition to the body dynamics, the fabric properties, specially the extension under tension, are also key factors for deciding the amount of ease for garments (Ziegert and Keil, 1988). Especially for close-fitting garments, fabric extensibility may directly impact on the comfort and freedom of movement of the wearer. Considering this, a guideline for selecting minimum ease based on fabric extensibility will be beneficial for pattern technicians.

3D virtual design of clothing as a part of the 3D-to-2D pattern unwrapping process requires the definition of both functional and styling eases at the design stage. Wang, Wang and Yuen (2002) defined a space between the virtual body and the 3D design. Hinds and McCartney (1990), McCartney et al. (2000) and Siegmund et al. (2010) determined offset points of the virtual body to apply ease to virtual clothing. It is apparent that a lot of offset parameters over the body are required to define virtual outerwear. In the established process of clothing engineering, ease is distributed over the girth measurements of a body (Beazley and Bond, 2003).

2.7 Pattern Grading

Traditionally clothing patterns are drafted in a base size. For the purpose of mass production of ready-to-wear clothing, it is necessary to develop patterns for all sizes of clothing within a size range. This is done by enlarging or reducing the patterns of the base size. The process for doing this is known as 'grading' within the clothing industry. Taylor and Shoben (1990) classified manual grading systems for flat patterns as either 2D or 3D grading systems. According to them, a 2D grading system only imparts two dimensional changes such as changes in girth and height whereas a 3D grading system makes changes in shape as well as girth and height. To incorporate changes in shape, a 3D grading system includes suppression grading (the dimensional changes in darts, seams, pleats and gathers which control the shape and contour of a garment). Schofield (2007) reported that 2D and 3D grading systems were termed as 'simplified' and 'complex' grading system respectively by Moore, Mullet and Young (2001).

Taylor and Shoben (1990) described the 3D grading system for flat pattern pieces as the optimum system and recommended it for use whenever possible. They suggested the skill of the grading technician, the types of garment, the number of sizes in a range and the types of fabric as the primary criteria for consideration when selecting a grading system. 3D manual grading is a skillful task and it is recommended for skin-tight garments as suppression grading plays a big role in garment shape. Whereas for loose-fitting and semi-drape garments, the value of adjusting suppression decreases and as a result, a 2D grading system can be used with no risk in respect of garment fit. However if the number of sizes in the range is large, a complex grading system is suggested. Stretch fabrics that readily conform to body shape are viable for being subjected to a 2D manual pattern grading system. When non-stretch fabrics are in use for garment making, a 3D manual grading system of patterns is preferable.

There are several techniques for implementing manual grading systems in practice. Taylor and Shoben (1990) mentioned two techniques: the draft or multi size (nested) grade, and the track or single size grade. Schofield (2007) identified three basic types of grading technique: shifting, proportional grading and edge changes. From the description given by Taylor and Shoben (1990) and Schofield (2007), the shifting technique and the track grade technique are synonymous; and the proportional grading and the draft grading are synonymous. Cooklin (1990) termed proportional grading as vector grading which is also sometimes called the master grade method.

The process of grading starts with the identification of zero points of reference (0,0) and grade points or cardinal points on the base pattern. Cardinal points are the specific points on the patterns which are subject to inward or outward movements to produce the boundary pillar for another size according to a calculated increment or decrement. Figure 2-24 shows the cardinal points and the zero lines of a basic bodice pattern.

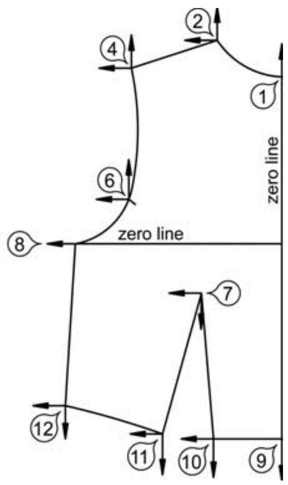


Figure 2-24 Cardinal Points 1 to 9 of a Basic Bodice Pattern (Schofield and LaBat, 2005)

In the shifting or the track grade technique, a stiff cardboard pattern is moved along the horizontal and vertical planes manually or with the help of a manually-operated grading machine on a table as can be seen in the Figure 2-25, based on the pre-calculated grade increments, and the outline around the base pattern is traced on paper in a new position to get the pattern for another size. Solinger (1988) termed this as the "track-shift" method. Figure 2-26 shows an example of track-shift grading of a shirt panel.

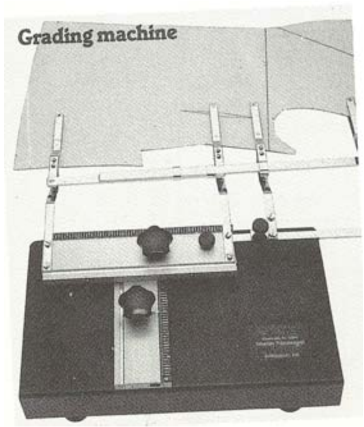


Figure 2-25 Manual Grading Machine (Cooklin, 1990)

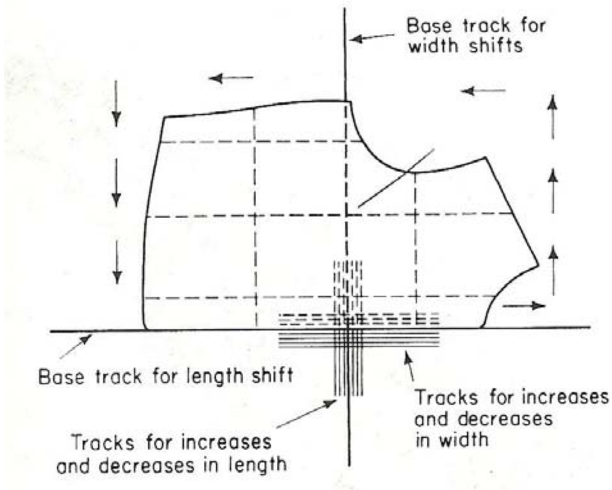


Figure 2-26 Example of Track-shift Pattern Grading (Solinger, 1988)

In proportional or vector grading, the cardinal points of a pattern piece of the largest size or the smallest size are first determined based on the cardinal points in the base pattern. Then the cardinal points of the base size patterns are connected by diagonal lines to the corresponding cardinal points of the largest or the smallest sized pattern, as illustrated in the Figure 2-27. Each of the diagonal joining lines is then divided into the number of intervening sizes, and marked to derive cardinal points of all other sizes in the size range. New patterns are then drawn from point to point.

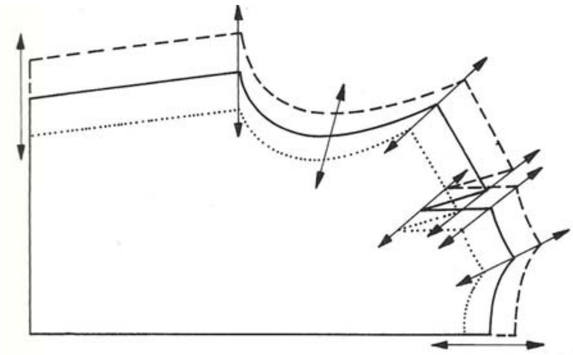


Figure 2-27 Example of Proportional Grading (Cooklin, 1990)

The edge-changes technique is a more recent development in pattern grading methods. This technique works based on grade rules. The grade rules are the displacement positions of the cardinal points represented as Cartesian coordinates (X, Y). The edge-changes grading forms the foundation of current computer-aided grading methods (Schofield, 2007).

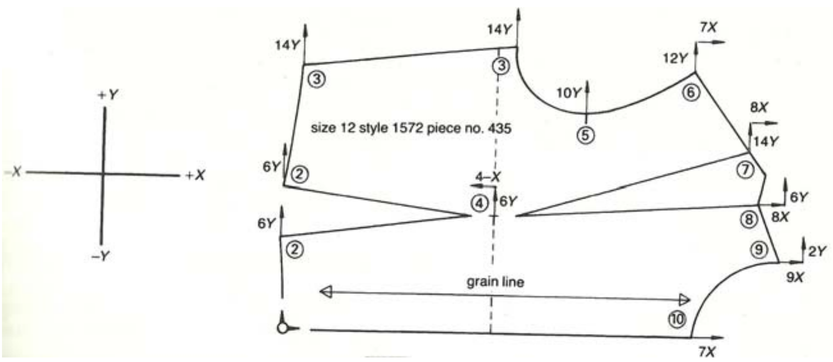


Figure 2-28 Preparation of Pattern with Grade Rule numbers for Computer Grading (Taylor and Shoben, 1990)

The manual process of grading is very time-consuming and heavily dependent on the grader's efficiency and expertise (Liu and Harlock, 1995). Available 2D clothing CAD systems that support grading are also not free from limitations although they offer time-saving solutions. The grade rules that are used by these systems to complete the grading process rely on manual calculations and inputs (Liu and Harlock, 1995).

With the development of 3D clothing design technologies, ideas of grading virtual clothing in space have also started to develop. Wang, Wang and Yuen (2002) presented a concept of grading virtual clothing by constructing the same garment on differently-sized virtual human models as may be seen in Figure 2-29. Although their process is a time-consuming and repetitive one as the same garment has to be repeatedly constructed on different-sized virtual models, they have pioneered the concept of grading virtual clothing in space and then extracting flat patterns of different sizes. A better alternative which, converts the virtual model from one size to another after designing a garment only once is later presented by Sayem (2004) and Roedel (2008). This approach requires the use of a virtual model which has been parameterised with the size data; grading can be done just by incorporating the appropriate size tables.

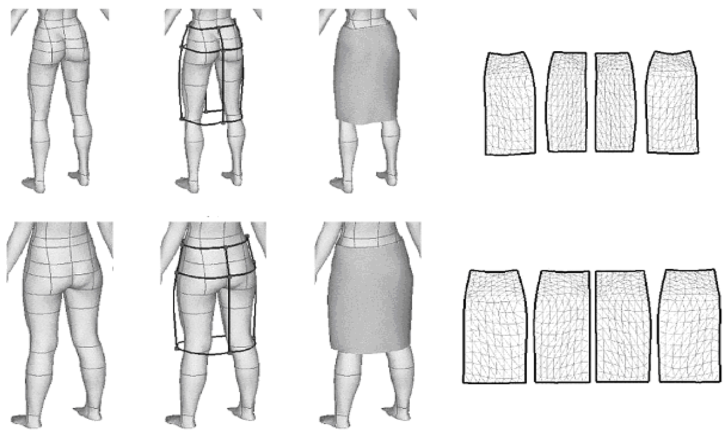


Figure 2-29 3D Grading on Virtual Mannequin presented by Wang, Wang and Yuen (2002)

Chapter 3: Research Methodology

3.1 Division of Tasks

This research aims to develop design platforms for virtual outerwear for the purpose of pattern flattening. It is intended to develop two resizable 3D templates; one for men's shirts another for men's trousers as upper body and lower body men's garments respectively. Major tasks of this research can be broadly categorised into two groups, such as:

1) development of the resizable templates;
2) demonstration of the functionality of the templates.

3.2 Selection of Methods

Figure 3-1 presents the planned workflow of this research project. The following techniques have been selected to perform the first group of tasks:

- Reverse Engineering (RE) of virtual models from body scan data (Point Clouds) and extraction of appropriate sectional curves from them;
- modifying and scaling the sectional curves, and performing geometrical modelling of the proposed design templates from the scaled curves.

RE is a technique for creating a digital clone of a physical object (Lee and Woo, 2000; Varady, Martin and Cox, 1997 and Yu et al., 2011). It is also termed as "Digital Shape Sampling and Processing (DSSP)" (Fu, 2007). It has a well-established application in creating CAD models from the surface data of objects as a part of product-development and rapid prototyping (Zhang, 2003; Chen and Ng, 1997; Lee and Woo, 2000 and Yu et al., 2011). According to Varady, Martin and Cox (1997), RE consists of four basic phases, namely: surface data acquisition, pre-processing, segmentation and surface fitting, and CAD model creation. There are established contact and non-contact methods for data acquisition targeting RE. However, nowadays, non-contact scanning devices have become very popular due to their capability for very quick data acquisition.

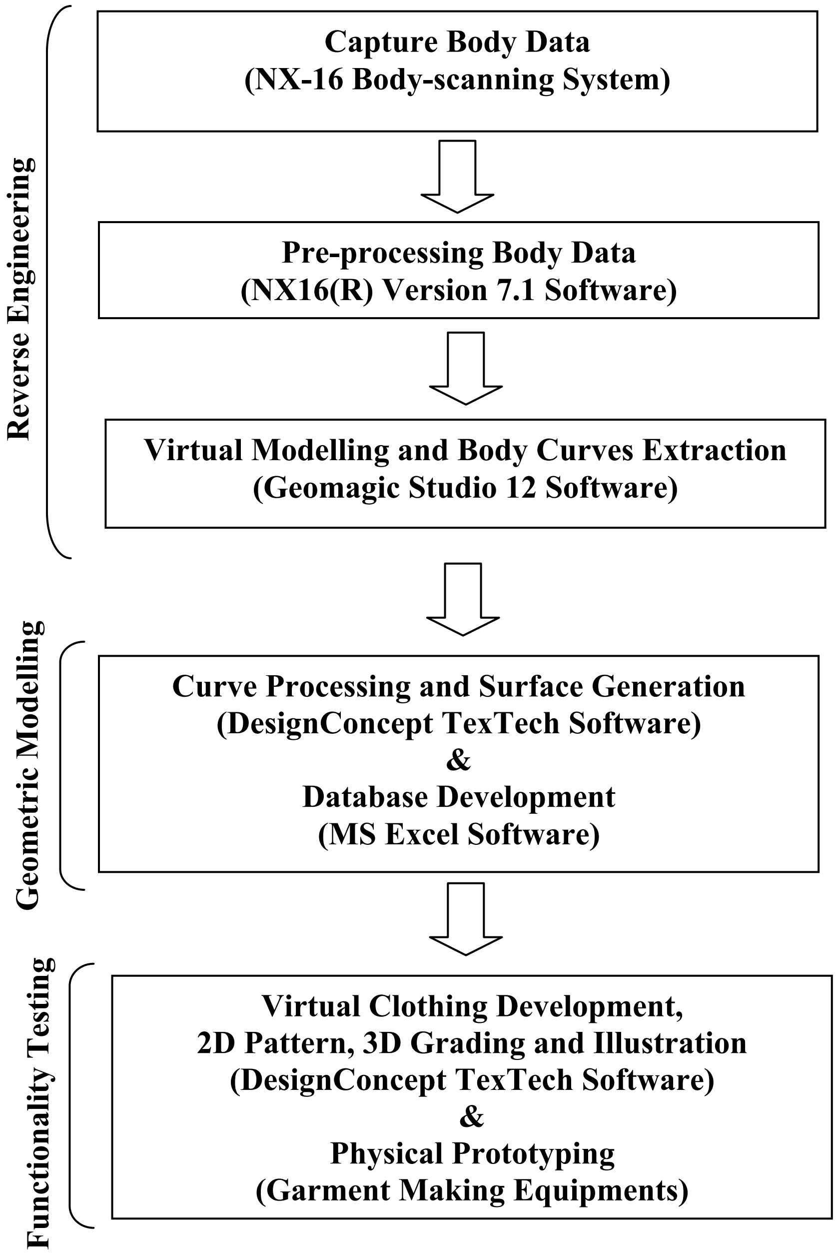


Figure 3-1 Planned Workflow of this Research Project

Body-scanners have found extensive application in sizing surveys and also in RE of virtual mannequins (Kim and Kang, 2002 and Seo and Thalmann, 2004, Cho et al. 2005). Au and Yuen (1999) described a RE process for a mannequin using a co-ordinated measuring device with a laser scanning unit. An NX-16 body-scanning system from [TC]² (Textile/Clothing Technology Corporation), USA was selected for use in this research to capture body surface data of living human models. Scan data of two male subjects were used as the basic input in this research. For the purpose of developing the upper body outerwear template, a set of body data from a male subject were captured using the NX-16 body-scanning system made available by the courtesy of [TC]². For the purpose of developing the lower body outerwear template, a male subject was scanned using the NX-16 body-scanning system available within the University. In both cases, the raw scanned data is first processed with the [TC]² 3D Body Measurement Software "NX16(R) Version 7.1" prior to further manipulation with other software suites.

The preprocessed data were then imported into the RE software "Geomagic Studio (GS)" from Geomagic Inc. (USA) in order to develop CAD models, which are the virtual representations of the exact geometry of the scanned subjects. In order to develop the resizable templates for the outerwear within the framework of this research, these CAD models were not used directly, rather a set of sectional curves are extracted from them. These sectional curves were further processed and used in the geometrical modelling of the proposed design templates.

The extracted sectional curves were imported into the 3D CAD software named "DesignConcept TexTech (DCTT)" from Lectra (France). As the human body is not exactly anthropometrically symmetrical, these curves also exhibited certain asymmetry in some respects. The curves were modified and made symmetrical by taking the geometry of basic outerwear into account. These modified and symmetrical curves form the basis of scaling and linking processes when used with size databases that include body measurements and ease allowances. A method for scaling construction curves with a single factor only in horizontal plane was described by Sayem (2004) and Roedel (2008). A modified process that includes a combination of single factor and multifactor scaling both in horizontal and vertical planes was implemented in this work targeting virtual outwear design, and a provision for ease allowance was included in the size databases which were programmed to be linked as a source of external parameters with the scaled curves. Finally parametric surfaces were generated out of the scaled curves to form the target resizable design templates.

The major part of the second group of tasks mentioned in section 3.1 was also implemented in the CAD software package DCTT. Using the available tools for 3D drawing, mesh generation and graphical rendering, designs of virtual outerwear were developed on the resizable templates. The flattening tool is exploited to develop 2D pattern pieces out of 3D designs. Resizability of the design templates and automatic grading of virtual clothing were tested by linking the different size databases using the Excel-linking capability provided within the software.

3.3 NX-16 Body-scanning System

The NX-16 3D body-scanning system is the latest and most efficient version of body-scanning system available from [TC]². Figure 3-2 shows the external and internal constructions of an NX-16 body-scanner. The system includes a scanning cabinet with sixteen non-moving scan heads and a computer system together with [TC]² 3D Body Measurement Software "NX16(R) Version 7.1". Tables 3-1 and 3-2 present the specifications and operational parameters of the NX-16 body-scanning system.

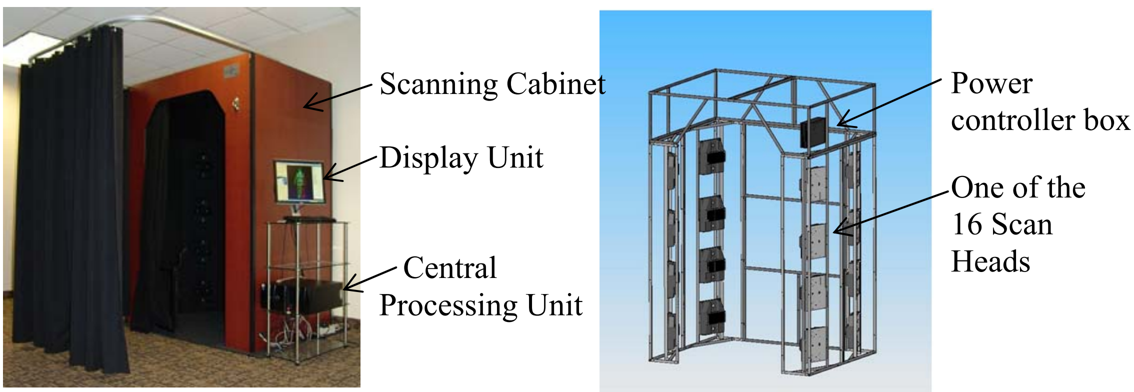


Figure 3-2 External (*Left*) and Internal (*Right*) Constructions of the NX-16 Body-scanning System

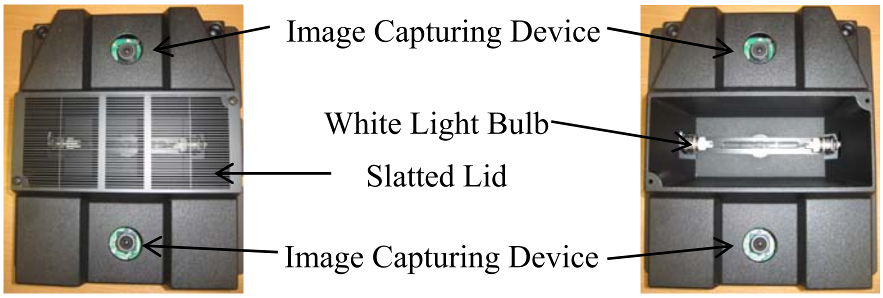
Table 3-1 Specifications of NX-16 Body-Scanning system

Power	15 amp (one outlet)
Technology	White-light, non- moving scan heads
Operation System	Windows 7

Table 3-2 Operational Parameters of NX-16 Body-Scanning system

Point Accuracy	<1 mm
Circumferential Accuracy	<3 mm
Data Point Grid Density	2x2 < mm
Scan Duration	8 seconds
Data Density (per subject)	600,000—800,000 points
Scan Volume (height X width X depth)	2 m X 1.2 m X 0.7 m

The NX-16 is a white light-based scanning system. Each scan head consists of one light projector and two image capturing devices (Figure 3-3). The light source in each scan head is covered with a perforated lid, as can be seen in Figure 3-3, which creates a structured light pattern when the light bulb is on. According to the [TC]^2 NX-16 body scanner tutorial manual, during the scan process, each of the scan heads projects a structured light pattern onto the subject and captures a series of images of the subject (TC^2 Tutorial, n.d.). The proprietary software then processes these images and converts them to thousands of data points to produce a raw image, representative of the shape of the subject, known as a "3D Point Cloud". The 3D raw data Point Cloud is a binary file and can be stored with a ".bin" file extension within the computer system. This raw Point Cloud is a composite version of all the images captured by the 16 scan heads and consists of overlapping multiple point data for a common single point of the body surface of the scanned subject captured by multiple scan heads. As a result, the size of the binary file is big, approximately 2 megabytes (TC^2 Tutorial, n.d.). This data file needs to be processed to produce a more refined body model of the Point Cloud, which can be used for virtual model generation and for accurate extraction of measurements. After the refining process, the data file is reduced to approximately 350 kilobytes and is stored as a reduced body data (rbd) format with the ".rbd" file extension.



With Cover *Without Cover*

Figure 3-3 The Scan Head

The scanning system should be calibrated before its first use and the calibration should always be verified first every time it is used for scanning any subjects. If the verification process reveals that the system is not within the calibration limits, a full system calibration is required to up-hold confidence in the Point-Cloud and the measurements it produces. The system comes with a calibration cylinder, two strings of calibration balls and a single ball. For the full system calibration, the cylinder and the balls are required to be scanned in any order. Then the software system compares the acquired data to the scanner internal calibration files to decide whether the calibration process has been successful or not. In case of the verification of the calibration, only the cylinder is required to scan. When the scanner is found to be within the calibration limits or the full system calibration is successful, it is ready to scan any subjects.

The scanning system offers both auto scan and manual scan options. In this work whenever the scanner was used, the auto scan option was selected and the Point Cloud data was stored with its ".rbd" file extension. The software system can extract body measurements directly and automatically from the ".rbd" data format. However the ".rbd" is not an open file format and it is not universally accepted by all RE and CAD software packages. For this reason, the refined point cloud data is further processed using an option called "Batch Process" available within the NX16 software system to covert it into an ".obj" file format, which is a geometrically definition file format and is an open file format adopted by many 3D graphics application vendors. During this conversion process, the Point Cloud data are transformed from point phase to polygonal phase and the ".obj" data feature a surface network of adjacent triangles, created between every three data points. The body model data in ".obj" is exported into the RE software “Geomagic Studio” used in this work for virtual model generation and sectional curve extraction.

Appendix 1 includes an overview of the user interface of the software “NX16(R) Version 7.1” and the list of the commands used in this work.

3.4 Geomagic Studio (GS)

GS is a software package that can create accurately surfaced 3D digital models from 3D scan data and polygon meshes for application in reverse engineering, product design and rapid prototyping (Geomagic, n.d). Version 12 of this Software, was received courtesy of the company named MD3D Ltd (UK), has been used for this research work. After the polygonal body models in “.obj” file format, prepared in the NX16(R) Version 7.1, have been imported into the Geomagic software package, it is necessary to repair any imperfections that exist in the polygon meshes before proceeding to surface generation phase. The GS software package offers a mesh correction tool named “Mesh Doctor” for both automatic and manual correction of the faulty meshes. The “Mesh Doctor” performs the following operations on the faulty meshes:

- a *remove spikes operation* that straightens a faulty polygon mesh by detecting and flattening single-point spikes;
- a *clean operation* that applies a shape-correction algorithm that relates the mesh to the underlying point set;
- a *de-feature operation* that deletes faulty triangles from the interior and inserts a more orderly mesh;
- a *fill holes operation* that repairs small voids in a faulty polygon mesh.

The “Auto-Repair” option available under the tool “Mesh Doctor” performs all of these individual operations in a single step. This option was always selected while using the mesh correction tool in this work.

Once the refinement of the polygon object is complete, the next step is to generate a smooth surface on the polygonal meshes. GS offers two options for surfacing, namely:

1) Exact Surfacing, and 2) Parametric Surfacing. As at this stage no parameter is going to be assigned on the virtual body model, the "Exact Surfacing" option was selected as the surface generation process. Again, under "Exact Surfacing", GS offers both automatic and manual surfacing options. When the automatic option "Auto Surface" was selected, it automatically creates a NURBS (Non-Uniform Rational B-Spline) model with minimal user interaction. This option was selected in this work to generate a NURBS surface on the refined polygon object resulted from Body Scan Data. The surface generation process in GS undergoes a sequence of sub processes (Geomagic2 n.d.):

- *generating panels* by sub-diving the polygon object into a number of panels based on contour or curvature lines;
- *constructing patches* within each panel;
- *constructing grids* within each patch;
- *applying a NURBS Surface* on the object with the help of the grids.

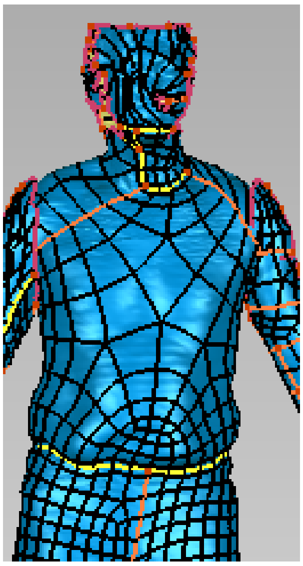
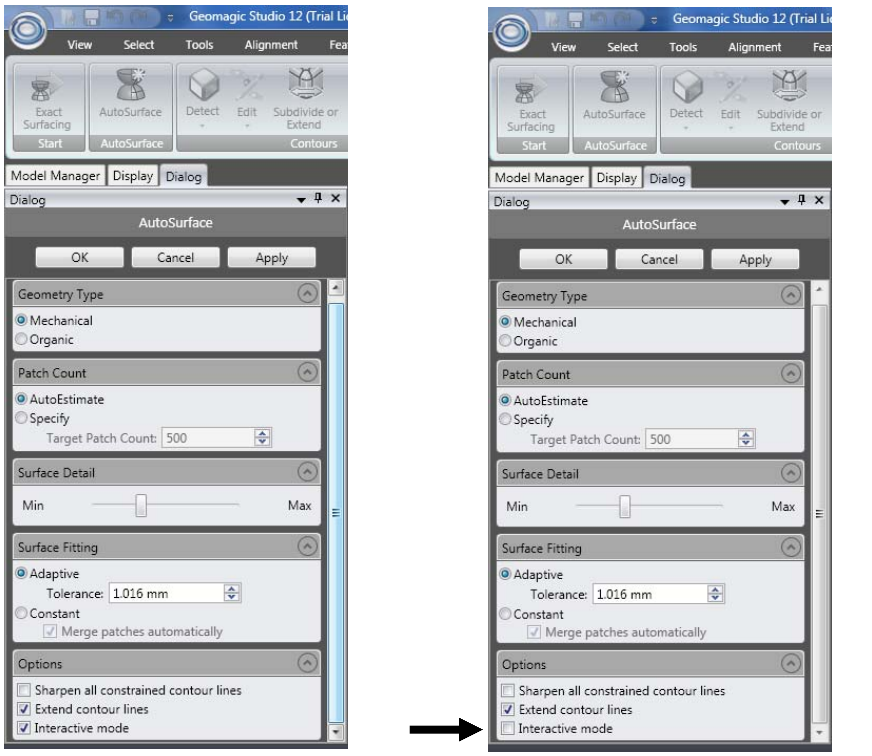


Figure 3-4 Patches formed during Surface Generation

As defined in the help menu of GS, "*a patch is a four-sided subdivision of a panel that is approximately equilateral*" and "*a grid is a set of rectangles that is placed into each patch*". Technically, the patches house the grids and the grids serve as a bed for the NURBS surface that is going to be generated in the next step. The precision of the ultimate NURBS surface depends on the density of the grids and the size of the patches.

Figure 3-4 for example shows the patches formed on a body model during the surface generation process. The “Auto Surface” operation under the “Exact Surfacing” tab performs all these sub processes one after another. While applying this operation during this work, most of the default parameters suggested by the software system, as appearing in the dialog box shown in Figure 3-5, are accepted with one exception; the “interactive mode” option is deselected. Deselecting the “interactive mode” that appears at the bottom on the dialog box ensures no further user’s intervention in surface generation process.



Default dialog box with suggested parameters

Accepted parameters with deselected “interactive mode” option

Figure 3-5 “AutoSurface” Parameters under “Exact Surfacing” Tab

After the completion of surface generation as a final step for the RE of a virtual mannequin, the surfaced object is converted into a CAD model using the “Convert to CAD object” tool available under the “Exact Surfacing” tab, and stored as an Initial Graphics Exchange Specification (IGES) data format. The IGES file format includes an “.igs” file extension and this is a vendor neutral data format exportable to the most of the available CAD systems.

In this work, the CAD models developed according to the above description were not directly exported into a 3D CAD system. Rather, a set of sectional curves representative of the body landmarks and measurement parameters for both the upper body and the lower body outerwear are extracted from these CAD models. Identification of the position of the necessary sectional curves and their importance are described in detail in the following chapters. The GS command used for the extraction of these sectional curves is the “Create by Section” available under the “Curves” menu. The extracted curves are also stored in the IGES file format, which makes ready to export into the 3D CAD software “DCTT” for further processing such as scaling and geometric modelling to develop the proposed 3D design templates.

An overview of the user interface of GS and the list of the commands used in this work are included in the Appendix 2.

3.5 DesignConcept TexTech (DCTT)

A brief description of the software package Design Concept Tex Tech (DCTT) is given in section 2.3.10 of the previous chapter. The application features of this software package, which have been used in the context of this research work, are described in this section. Version “V4R1c1” of the DCTT software package has been used in this work. It has four different working modes with four different user interfaces termed as “documents” within the software system. The four different types of document that are offered by this software package to work in are: 3D Design, 2D Pattern, 2D Product and 2D Draft document. Work done in these documents is also stored with four different file extensions, namely: “.top”, “.pat”, “.pro” and “.dft” respectively. An overview a 3D Design document is presented in the Appendix 3.

The 3D Modelling task behind this research work has been executed in a “3D Design” document. The IGES file containing the sectional curves extracted in the GS software was imported into a 3D design document of the DCTT. Using the spline curve drawing tool available under the “curve” menu of the DCTT, a set of modified curves was newly drawn based on the extracted curves. The modification of the curves’ structures was executed taking the surface geometry of a common item of upper body and lower body outerwear. However, the newly drawn curves are found not to be fully symmetrical because of their origin curves. The human body is not one hundred percent symmetrical. As a result, the extracted sectional curves also lacked symmetry, which was visually identifiable. However, clothing items are always made symmetrical unless the designer introduces any intentional asymmetric feature. Considering this, it was found necessary to make the drawn curves symmetrical. To do this, the newly drawn curves are divided into two equal halves, a left and right subset of the original curves, based on a vertical plane. This was achieved using the curve-trimming tool available under the "curve" menu. One half of each curve was then duplicated as a mirror image of the opposite half using the object duplication tool available under the "edit" menu. The selected halves of the curves were merged with their mirrored halves using the appropriate tool available under the "curve" menu to make a set of symmetrical closed curves. These modified and symmetrical curves were only used for the next step of the development of the 3D design template.

To ensure the resizability of the proposed design templates, the modified and symmetrical curves were scaled and programmed to link with external size databases. The scaling procedure involves creation of two parameters for each curve, selection of a scaling point for each curve and inputting one or more scaling factors for each curve. Two length parameters created for each curve can be termed as "*parameter_original*" and "*parameter_resize*", where the former one is defined with the existing length of each of the curves and the later is defined for any external values from a size chart. The ratio of "*parameter_resize*" to "*parameter_original*" of each curve forms the scaling factor for the respective curves for the size change in the horizontal plane. Where it is appropriate, a multi-factor scaling process is followed to ensure the resizability in both horizontal and vertical planes. The procedure is further explained in the next chapters. The "create parameter" tool available under the "parameter" menu is used for parameter creation; and the "duplicate" tool under "edit" menu with options "scaling from point" and/or "scaling with 3 factors" is used for the scaling operation.

The scaled curves were prepared for surface generation using geometric modelling techniques. The "loft" tool available under the "shape" menu offers different geometry matching options such as "curve to curve matching", "point to point matching" and "segment to segment matching", and different surface synchronisation options such as "parametric", "proportional" and "continuous". As it is intended to generate a new surface following the geometry of the scaled curves representative of the size parameters, a '*curve to curve matching*' option is selected. The '*parametric synchronisation*' option was selected to ensure the adaptability of the newly generated surface with the external size parameters when linked with size databases. The geometric models with their new surface form the proposed 3D design templates for outerwear.

As a part of the second task mentioned in section 3.1, the functionality of the resizable templates developed in this work were tested based on the following criteria:

a) function as a drawing platform;

b) 3D clothing development and flattening;

c) automatic grading of 3D clothing;

d) resizability.

The DCTT software offers the tools for drawing 3D curves and for generating a localised adjacent layer known as a "region" on the surface of any 3D object. According to the description provided in the "Help" menu of DCTT, "*A region is an entity that represents an approximation of part of a 3D shape; it consists of a triangular mesh, limited by one or more boundaries*" (DCTT-Help, n.d.). Using the tools for the region curve drawing and region creation from curves, designs of virtual outerwear are produced on the 3D templates. The DCTT software suite offers two modes for implementing region creation, namely: "Link-length-based region" creation and "Curvature-based region" creation, but for flat pattern extraction the former is suggested (DCTT-Help, n.d.). In link-length based region creation, the link-length and the vertex angle are two control parameters. However, the average length of the mesh links is the main region control parameter that influences the mesh quality, whereas the vertex angle determines the number of segments at the boundary line of a triangular mesh. In the case of link-length based region formation in DCTT, the link indicates the edge of each triangle in a triangular mesh but the selected vertex angle only controls the angle form at the corner points in the mesh boundary (DCTT-Help, n.d.).

In order to flatten the 3D design of outerwear into flat pattern pieces, a “2D pattern” document of DCTT is first opened and then the region-flattening tool, available under the “patterns” menu is used. The flattening operation involves two steps: first, the selection of the region part to be flattened, and second, the selection of flattening options appears in the “Flattening parameters” dialog box. In order to maintain the dimensional integrity of the flat pattern pieces, the “*Match edge lengths*” radio button is always selected, as shown in Figure 3-6.

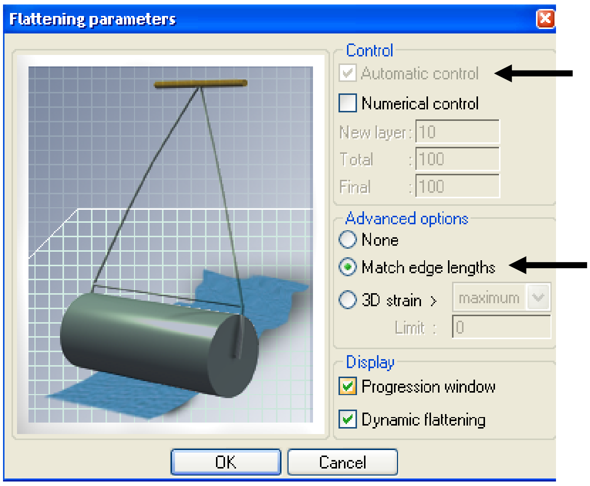


Figure 3-6 Flattening Parameter Dialog Box

The flattening tool provided by DCTT considers the geometric constraint of the shape, but no material properties. The process is comparable to the flattening of a network of springs whose stability is obtained through an even distribution of its internal energy (DCTT-Help, n.d.). It is an iterative process which proceeds layer by layer beginning from the flattening start point. To control the flattening process, DCTT offers both automatic and numerical options, as can be seen in Figure 3-6. The automatic control allows the flattening algorithm to run until balance is reached (DCTT-Help, n.d.). This option is always selected for pattern flattening throughout this research work.

To prepare the flattened pattern pieces for meaningful use in clothing manufacturing, an appropriate seam allowance is added around them. This is done in a “2D product” document using the “design parts” tool with the *“create seamline part”* option, which is available under the “parts” menu.

Rendering of the virtual clothing items developed on the 3D templates is performed by keeping both the "3D Design" document (containing the 3D template and virtual clothing design) and the "2D pattern" document (containing the flattened pattern pieces open). On the active "2D Pattern" document, the "create rendering" tool with a *"create virtual marker"* option available under the "Pattern" menu is used to apply different graphical images of a particular pattern piece. After doing that, when the "realistic rendering" option in the "rendering" tab is activated, the graphic image applied on the pattern pieces is visualised in 3D.

3D Grading of virtual clothing and the resizability of the 3D templates are tested using the "Excel link" and "Edit list" tools available under the "Parameter" menu.

The list of the DCTT commands used in this work is given in Appendix 3.

3.6 Microsoft (MS) Excel

The MS Excel spreadsheet programme is used to create the size data-bases to facilitate 3D grading using the proposed 3D templates. DCTT software, which is built on the TopSolid CAD system, can accept external values for parameters from Excel sheets. To do this, the cell of an Excel database, which contains the desired value of a parameter, has to be assigned as "TOP_X", where X is the parameter designation used in DCTT. For example, if the parameter designation for neck girth is "Ng_ST", the Excel cell, which contains the value for this, should be assigned as "TOP_Ng_ST". Figure 3-7 demonstrates an example of this procedure for the Excel cell "D3" that contains the neck girth measurement (42 cm) and has been assigned as "TOP_Ng_ST" in the name box.

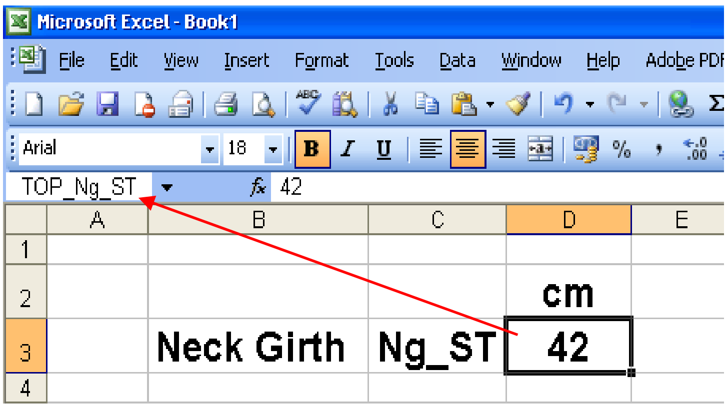


Figure 3-7 An Example of Assigning Parameter Designation in Excel

The same procedure is followed for each and every size parameter relevant to shirt and trouser templates to develop the size databases.

3.7 Computer System and Printer

The reverse engineering and geometric modelling part of this research work was carried on a computer with following specification:

Intel (R) Core ™ 2 Duo processors (E7400 @2.80 GHz, 2.79 GHz);

4 GB of RAM;

Microsoft XP Professional Version 2002 (32-bit Operating System).

The flat pattern pieces were printed by a HP LaserJet 1320n printer.

3.8 Machines and Materials

A single-needle lock stitch machine “Mitsubishi LS2-190” and a three-thread over-edge stitch machine “Brother EF4-B511” have been used for stitching physical prototypes based on flattened pattern pieces.

A 100% cotton knitted fabric and a 100% linen woven fabric, both purchased from the local market, were used for making physical prototypes. 100% polyester sewing thread (27 Tex and Ticket Number 120) was used for stitching the prototypes.

Chapter 4: Resizable Shirts Template

4.1 Workflow

The process followed to develop a resizable shirt template is summarised in Figure 4-1 and further described in the following sections.

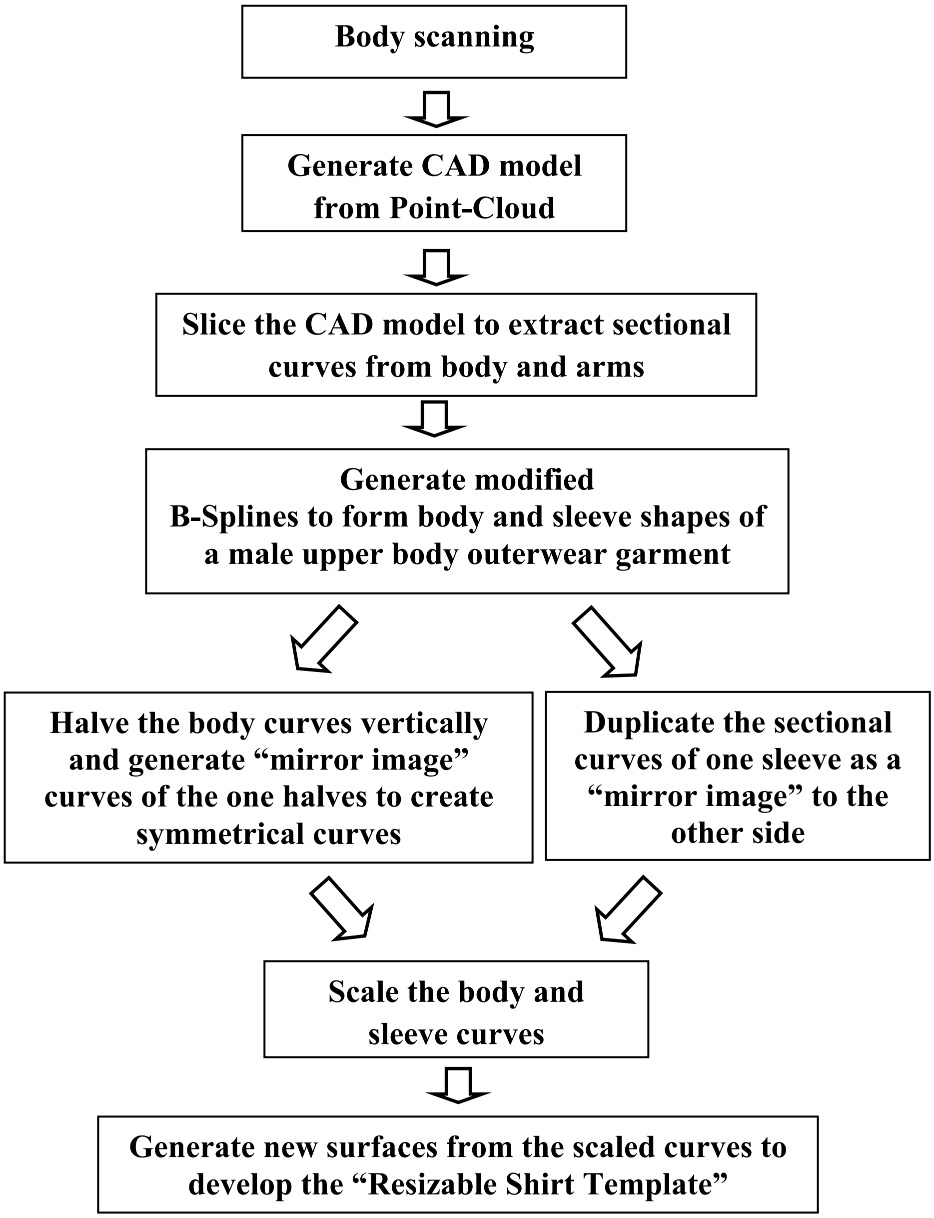
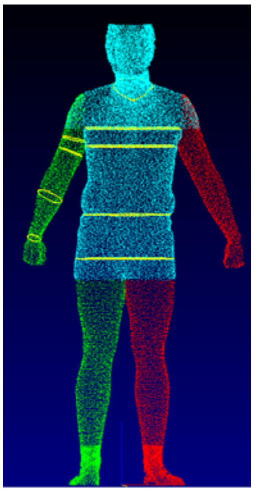


Figure 4-1 Workflow for Resizable Shirt Template

4.2 CAD Model from Point-Cloud

The Point-Cloud data captured from a full-body scan of a mature male subject has been used as the primary input to produce the proposed resizable shirt template. The relevant body measurements extracted from the scan data using the NX16 proprietary software are summarised in the Table 4-1.

Table 4-1 Body Measurements of the scanned Subject

Measurement Positions			**Measurement in cm**
	1	Neck girth	44.1
	2	Shoulder girth	94.7
	3	Chest girth at armpit level	108.1
	4	Chest girth at the fullest area	105
	5	Waist girth	99.9
	6	Hip girth	105.5
	7	Upper arm girth	34.2
	8	Arm girth on Bicep	33.2
	9	Forearm girth	30.4
	10	Wrist girth	18.3
	11	Height	180

The scan data was received from the NX16 analytical software as a refined body model in ".rbd" file format. Figure 4-2 illustrates the Point-Cloud data of the male subject in this file format. The scanning units in the NX16 scanning cabinet, which are located in four columns, capture surface data off a subject from its front and back. There is no scanning unit located either at the top, bottom or on the lateral sides of the cabinet. As a result, there are significant areas from which no information is captured and therefore included in the Point Cloud data, and this is clearly shown in Figures 4-2 and 4-3. However, this localised shortage of data points does not interfere with the further processing the data to connect the points with each other to form a network of triangles. Figure 4-3 represents the triangulated body model in ".obj" data format which is ready to export into the RE software. At this stage, the body model consists of approximately 110,000 triangles and a surface area of 1985,440 mm^2.

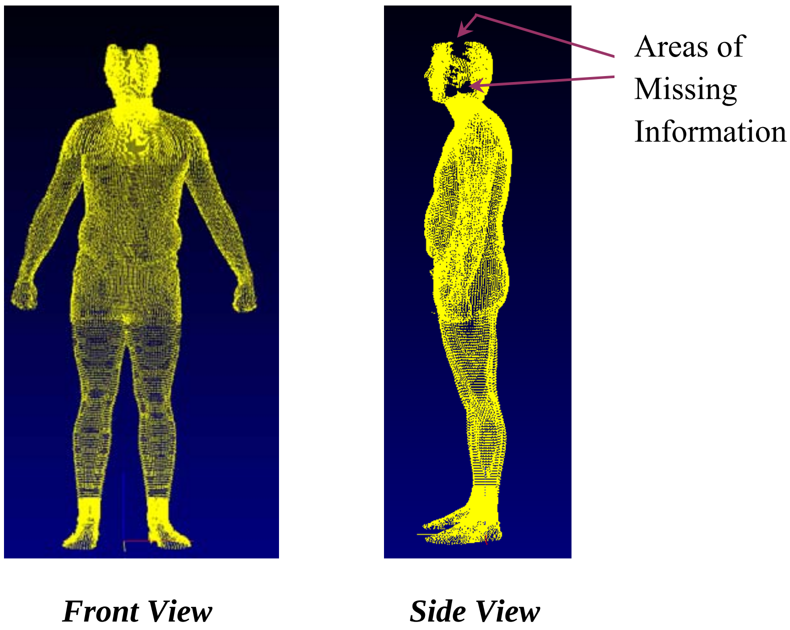


Figure 4-2 Illustration of the Point-Cloud data of the Male Subject

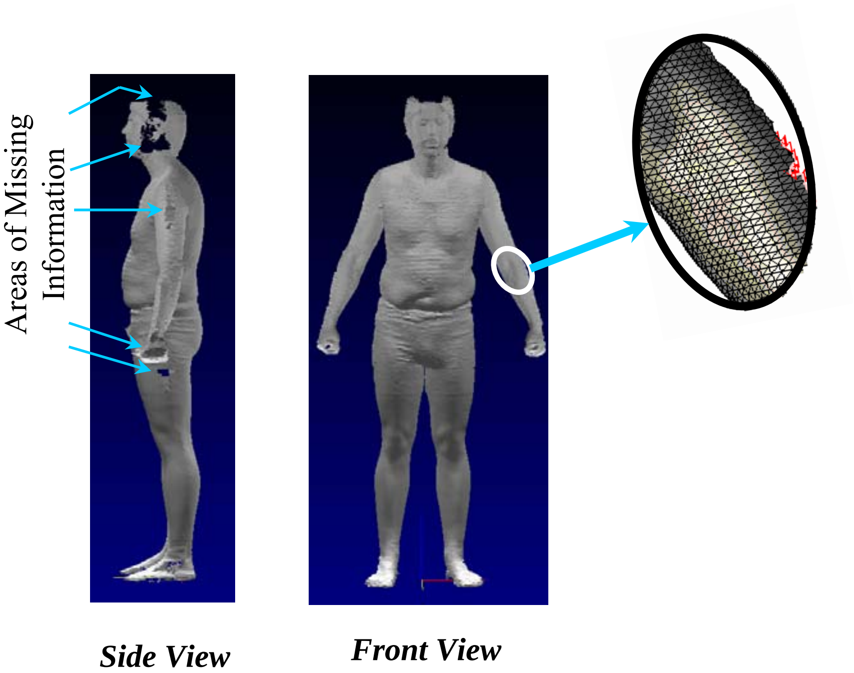


Figure 4-3 The Body Model in Polygonal Phase

Using the RE software the triangulated body model is converted into a CAD model, which is used for extracting the sectional curves from it. This CAD model is formed by 400,000 mesh triangles. This model is ready to be exported into virtually any CAD system. However, instead of exporting this directly to another CAD system, a set of sectional curves was extracted from it. The extracted curves were subsequently exported into a 3D CAD system for further processing.

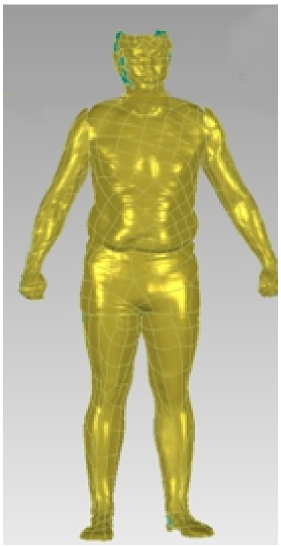


Figure 4-4 The CAD Model

4.3 Sectional Curve Extraction

The proposed resizable design template was intended to be structured around a set of sectional curves, which are representative of the size parameters. The positions of these necessary sectional curves were first identified on the digital body model at pre-determined horizontal and inclined displacements. Primarily seven sectional curves from the torso and three from each of the arms were extracted, as can be seen in Figure 4-5. Later two more arms curves were derived from two of the body curves in order to form the complete structure of the sleeves of the proposed shirt template.

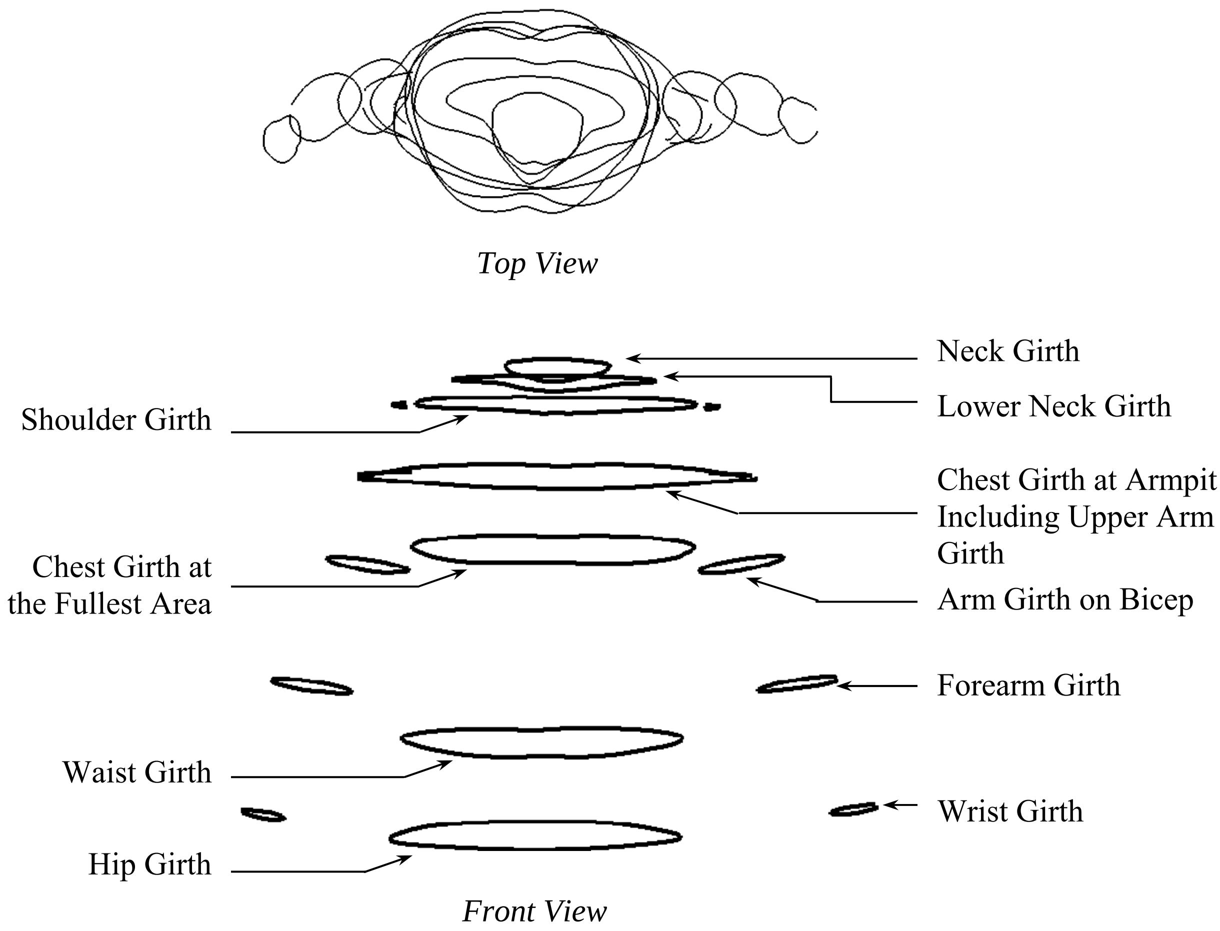
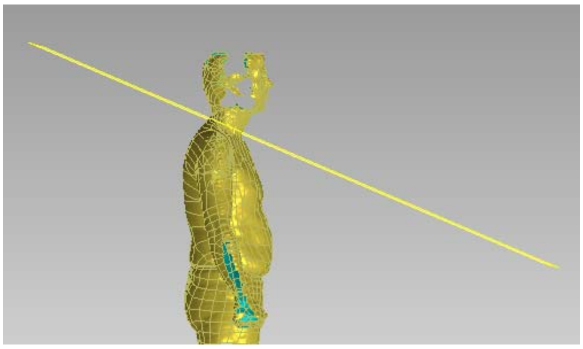


Figure 4-5 The Extracted Sectional Curves

4.3.1 Curves from the Torso

The European Standard for size designation of clothes “EN 13402-1:2001” was consulted to identify the positions of the landmark positions of the four primary sectional curves representative of the neck girth, chest girth, waist girth and hip girth. According to the EN 13402-1:2001, the neck girth is located 2 cm below the laryngeal prominence (the Adam’s apple) and at the level of the 7th cervical vertebra (the nape of the neck). Using an inclined plane, as illustrated in the Figure 4-6, the neck girth was identified on the body model within the GS software. Other than the neck girth curves, the positions of all other body girth curves were identified exactly on horizontal displacements.



Side view of the Inclined plane on Neck Girth Position

Neck Girth Position According to the EN 13402-1:2001

Figure 4-6 Identification of the Neck Girth on the Body Model

As described in the EN 13402-1:2001, the chest girth is the maximum horizontal girth measured over the scapulae (shoulder blades), under the axillae (armpits) and across the chest. Analysis of the Point-Cloud data, which are in use in this work, by the $[TC]^2$ body measurement software reveals that the maximum horizontal girth across the chest is found just under the armpit (see Table 4-1). Based on this information, the chest girth position on the body model was identified using a horizontal plane.

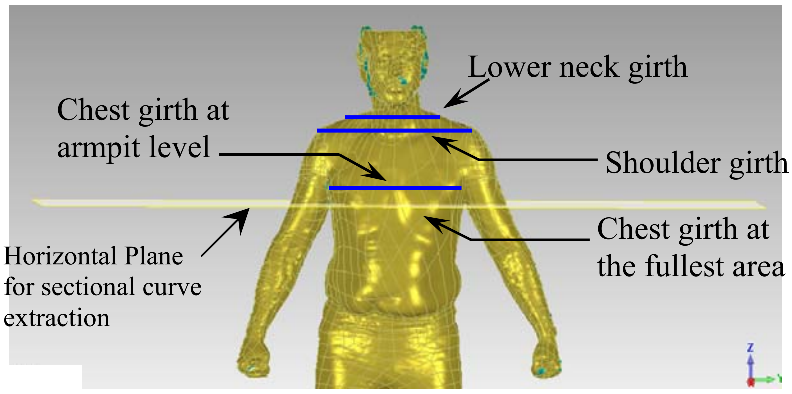


Figure 4-7 Positions of Chest Girths, Shoulder Girth and Lower Neck Girth

The measurements of waist girth and hip girth are not directly used in the traditional pattern cutting system for men's shirts (Aldrich, 1990). However, the position of the waist line is important for shaping and tailoring the middle part of the body of shirts and jackets (Aldrich, 1990). Figure 4-8 shows examples of tailored men's shirts, in which the concave silhouette is associated with the position of the waistline. The waist girth curve was selected in this work with the aim of maintaining an option to produce a tailored silhouette of men's shirts on the proposed design template; and the hip girth curve was selected as its lower end contour.

Figure 4-8 Example of Men's Shirts Tailored based on Waistline Position

According to EN 13402-1:2001, the waist girth is taken to be the natural waistline between the iliac crest (the top of the hip bones) and the lower rib; and the hip girth is the horizontal girth with the maximum circumference measured round the buttocks. Based on this information, the positions of these two girths are identified on the CAD model using two horizontal planes.

In addition to the four primary sectional curves, three secondary curves (two for the "neck to shoulder" area and one for the chest area) were found to be necessary to accurately reproduce the geometry of upper body garments. These girth measurements are not traditionally used as size parameters, because they do not correspond with easily identifiable anatomical landmarks. As a result, no available standard describes their positions on the torso.

For rebuilding the "neck to shoulder" area, two secondary girth curves, namely the lower neck girth and the shoulder girth were incorporated. The shoulder girth curve was located at approximately 1 cm below the crown of the shoulder on either side of the torso. The lower neck girth is designated as being 3 cm above the shoulder girth.

To rebuild the geometry of the chest area, a second girth measurement at the fullest chest area, as shown in the Figure 4-7, was selected.

4.3.2 Curves from the Arms

In order to develop the sleeves of the proposed 3D template, four curves, namely: the upper arm girth, the arm girth on bicep, the forearm girth and the wrist girth are used. Of these, only the wrist girth is sometimes used as a size parameter in traditional pattern cutting systems (Aldrich, 1990). The other measurements do not correspond to easily-defined anatomical landmarks; they do not lend themselves to repeatable manual measurement. Consequently, no size standard describes the position of the arm girth measurements. However, with the availability of body scan data, it is possible to specify and take advantage of non-standard anatomical measurements, as they can offer useful secondary measurements. As previously (with the chest girth measurements), the circumferential sections through the arm have been selected through optimal visual observation. These girth measurement positions were located on the CAD model where they were found to offer the most favourable data for the reproduction of the sleeve geometry in respect of the proposed 3D design platform. The forearm girth was located on the fullest area below the elbow, and the upper arm girth on bicep was located at approximately 5 cm above the elbow joint, as shown in the Figure 4-9. The curves representing the wrist girth, forearm girth and the upper arm girth were not extracted exactly on horizontal planes, rather on inclined planes shown in the Figure 4-9.

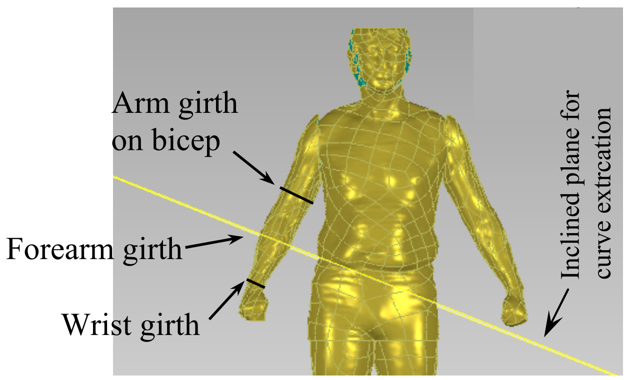


Figure 4-9 Positions of the Arm Girths

Due to the limitations of the scanning process and the arm positions of the male subject during scanning, the upper parts of the arms were found to be merged with the upper body part of the model after processing the scan data to form a triangulated surface mesh. As a result, the chest girth and upper arm girth at the armpit level are also found merged with each other. To address this problem, the upper arm girths were separated from the larger central section using geometric curve editing tools. This is further described in the next section.

4.4 Modified Curves Generation

The sectional curves, which are stored as an IGES data format, were imported into the DCTT software package. Naturally, these curves represent the surface geometry of a scanned subject, but do not necessarily provide a satisfactory shape for the surface geometry of an outerwear garment. Furthermore, they were found to be broken in some places due to limitations of the scanning and modelling processes. Using the curve drawing tool of the CAD system, continuous B-Spline curves were generated from each of the sectional curves by removing the irregularities in the extracted curves such as concave areas due to the natural geometry of the human body (for example the spinal cord line at the back of the torso) and by taking the geometry of men's upper body outerwear into account.

4.4.1 Curves Processing for the Body

While drawing the modified neck girth, the protruding parts at the front due to the laryngeal prominence were avoided as well as the concave segments both at the front and back which were smoothed out. The lateral concave segments of the lower neck girth curve were also smoothed out in the newly drawn modified curve. These modified curves are illustrated in Figure 4-10.

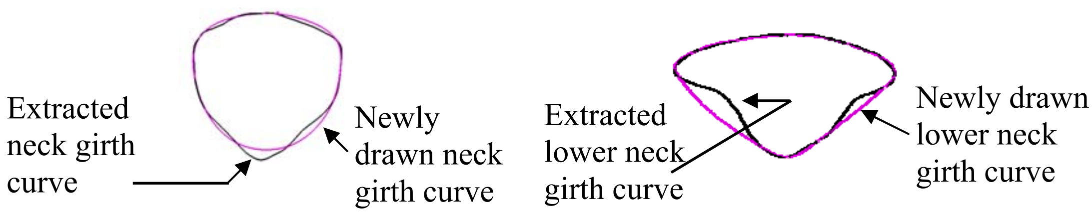


Figure 4-10 Modified Neck Girth and Lower Neck Girth Curves Generation

For the shoulder girth and the chest girth at the armpit, the concave segments were first covered with straight lines and then the modified closed curves were drawn over them reaching the furthest ends of the broken curves which lie on both sides of the extracted curves (see Figures 4-11 and 4-12). It can be noted that the newly drawn modified curves for the chest girth at the armpit level include the upper arm girths, which merge with them.

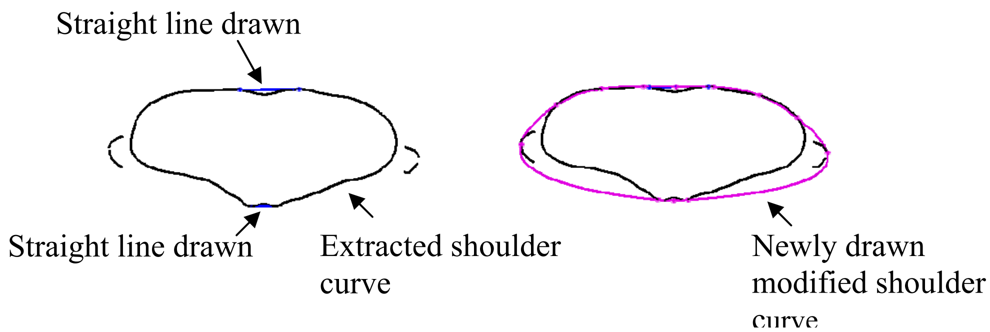


Figure 4-11 Drawing Modified Shoulder Girth Curve

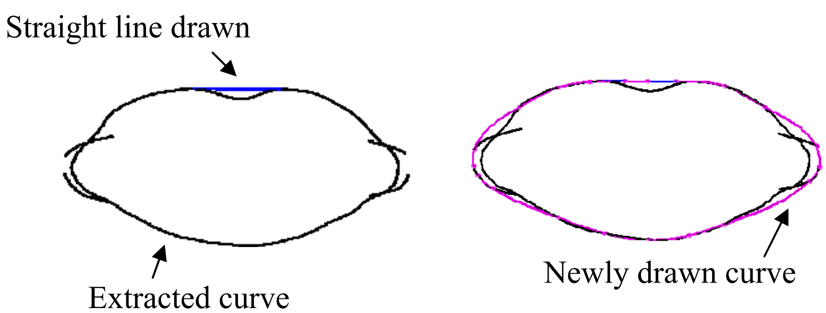


Figure 4-12 Drawing Modified Chest Girth Curve Including Upper Arm Girths

Similarly modified curves for the chest girth at the fullest area, waist girth and hip girth are drawn, as illustrated in the Figure 4-13.

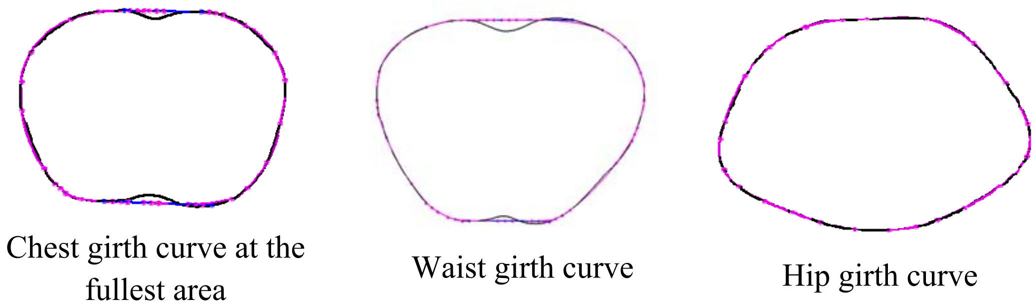


Figure 4-13 Drawing Modified Curves for Chest Girth at the Fullest Area, Waist Girth and Hip Girth

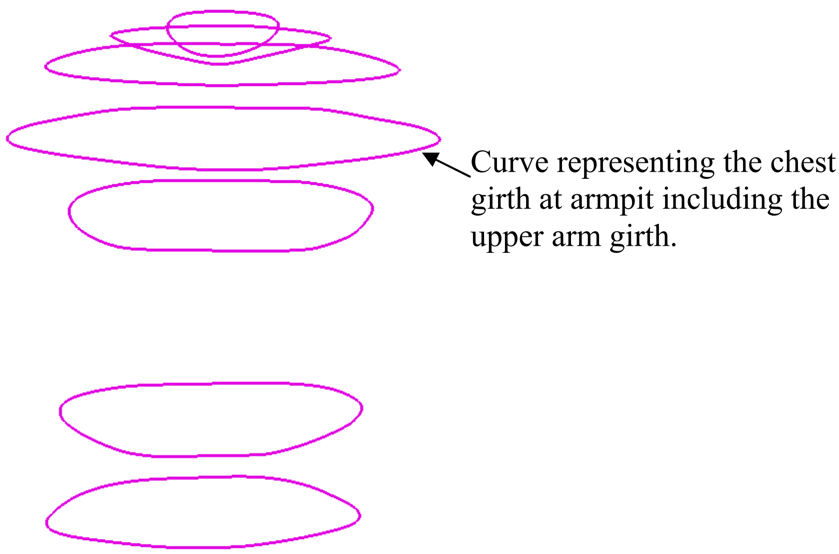


Figure 4-14 Modified Sectional Curves of the Torso

Figure 4-14 shows all the newly generated modified body curves which have been developed from the extracted sectional curves.

4.4.2 Symmetrical Body Curves Generation

The human body is not a symmetrical object, so the curves that are derived from it inevitably lack symmetry. Even the newly drawn modified curves inherit visible asymmetry from their parent curves. However, mass-produced clothing is expected to have a symmetrical structure if intentional asymmetry has not deliberately introduced by designers. This required the curves to be modified to meet the purpose.

The body curves were split into two halves based on a vertical plane. In order to generate fully symmetrical body curves, any of the left or right halves of the curves can be duplicated as “mirror image curves” to the other side using the curve duplication process available in the DCTT software. Before doing that, the upper arm girth was first separated from the chest girth at armpit level as described in the next section, 4.4.3. After that the left individual halves of the body curves were mirrored to generate fully symmetrical body curves, as illustrated in Figure 4-15.

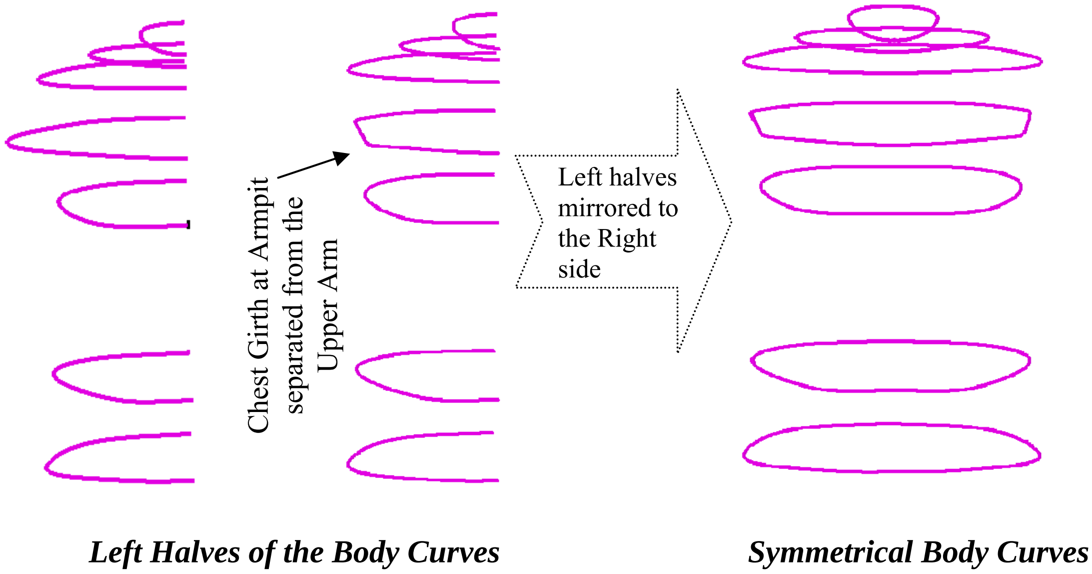


Figure 4-15 Symmetrical Body Curves Generation

After the mirror-duplication of the left halves of the body curves over to the right side, each of the left halves were joined with its respective mirrored curves to form completely closed and continuous curves. This generates fully symmetrical body curves. These symmetrical curves were further used in the subsequent steps of the process.

4.4.3 Curve Processing for the Sleeves

In order to separate the upper arm girth, a straight line for use as a separator was drawn on the left half of the chest girth at the armpit level following the lateral boundary of the chest girth at its fullest area underneath. The curve was then split at the places where the separator line touched it using the curve division tool. Both of the split parts were closed with straight lines and the sharp edges were smoothed out. The procedure is illustrated in Figure 4-16.

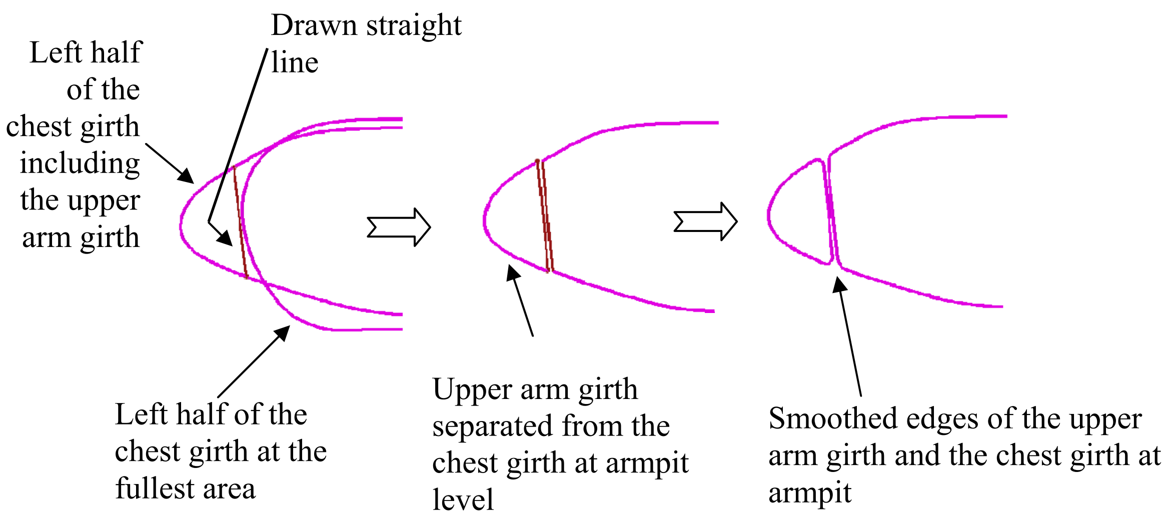


Figure 4-16 Procedure for Separating the Upper Arm Curve

To define the top edge of each sleeve, a small closed curve was generated based on the furthest end of the left half shoulder girth curve in a similar way to that in which the upper arm girth was produced. However this was done in a duplicated copy of the shoulder girth curve, so that the original shoulder girth curve would be retained intact. The newly produced curve to define the top edge of the sleeve is hereafter termed as Curve "TS".

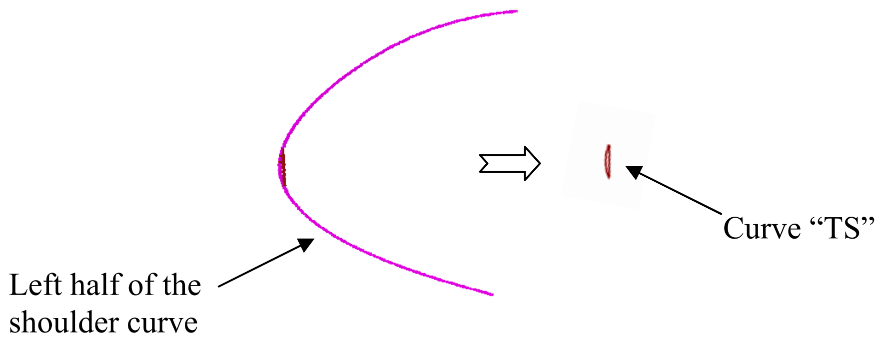


Figure 4-17 Deriving Curve "TS" from the Shoulder Curve

Modified closed curves for the arm girth at the bicep, the forearm girth and the wrist girth, as shown in Figure 4-18A, are drawn following a similar technique to that used to create the body curves described in section 4.4.1. However, it was later found that these newly drawn curves did not form acceptable sleeve geometry together with the upper arm girth and the curve "TS", due to their significant differences in shape. To overcome this problem, another set of closed B-Spline curves were drawn over them, as shown in Figure 4-18B.

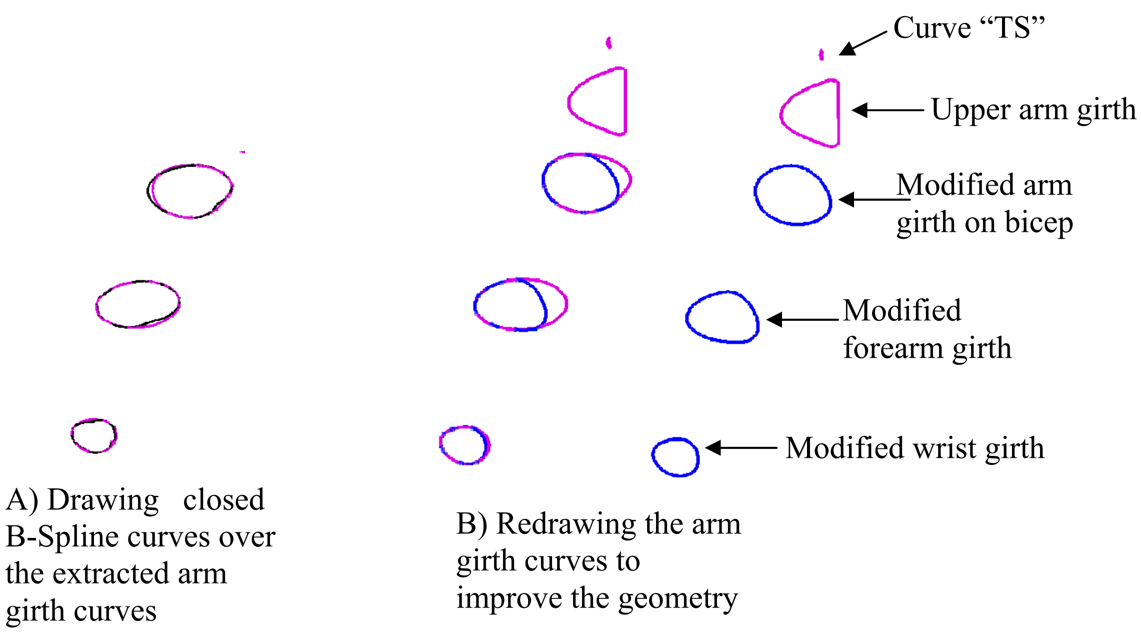


Figure 4-18 Generating Modified Arm Girth Curves

In order to ensure the symmetry of the proposed 3D design template, the newly-generated modified sleeve curves from the left side are mirrored to build the respective curves for the other side, hence creating symmetrical curves for the right and left sleeves.

4.5 Finalising the Body Curves

The resultant curves according to the procedure described in section 4.4 are illustrated in Figure 4-19. Before scaling the curves to ensure the resizability of the proposed shirt template, these curves were first tested by generating a surface out of them. The surface generation process is further discussed in section 4.7. The qualitative ability of the body curves to form appropriate geometry for a men's shirt is dealt here.

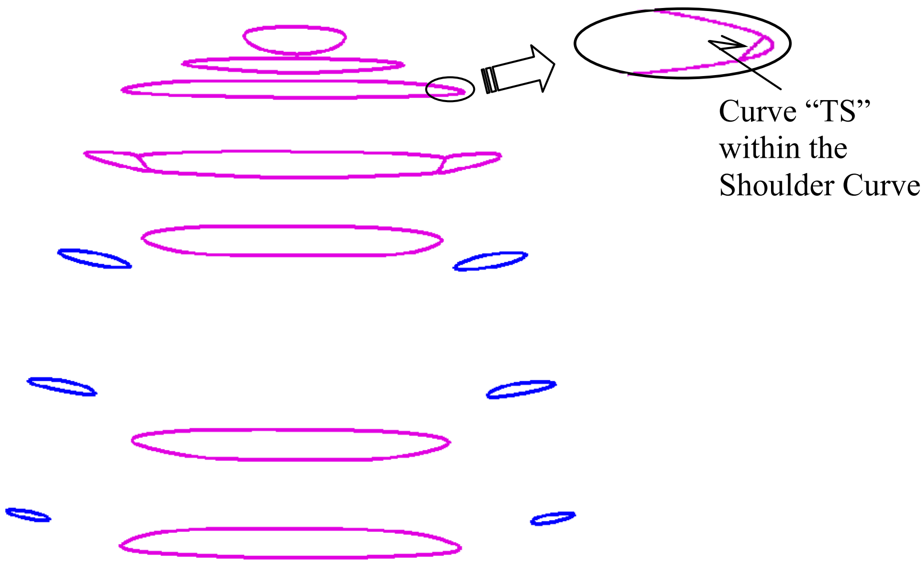


Figure 4-19 Symmetrical Body and Sleeve Curves

A close review of the curves representing the chest girth at the fullest area, waist girth and hip girth; reveals significant differences in their shape and depth. They do not produce a good body shape to represent standard shirt geometry, as can be seen in Figure 4-20. The resultant shape from these three curves has a convex outline at the front and a concave outline at the back, when seen from the sides.

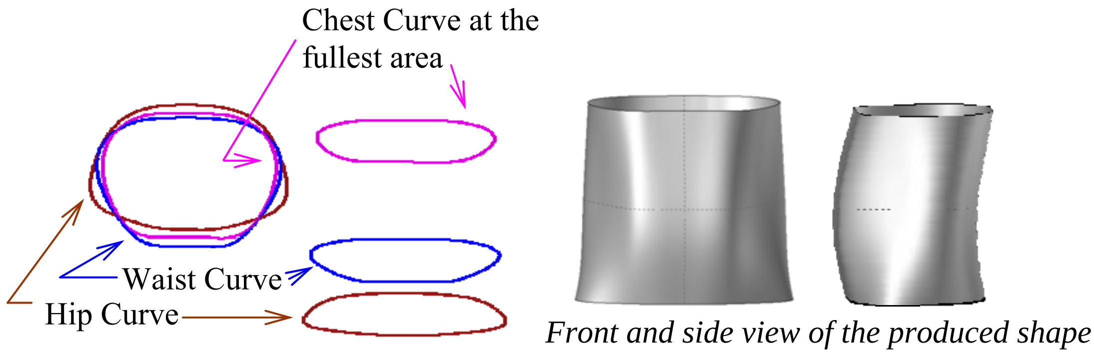


Figure 4-20 Differences in Curve Geometry and the produced Shape

To address this problem, the waist curve and hip curve were replaced by duplicated copies of the chest curve. Because they utilise the same curve geometry, they form a uniform body shape as can be seen in Figure 4-21.

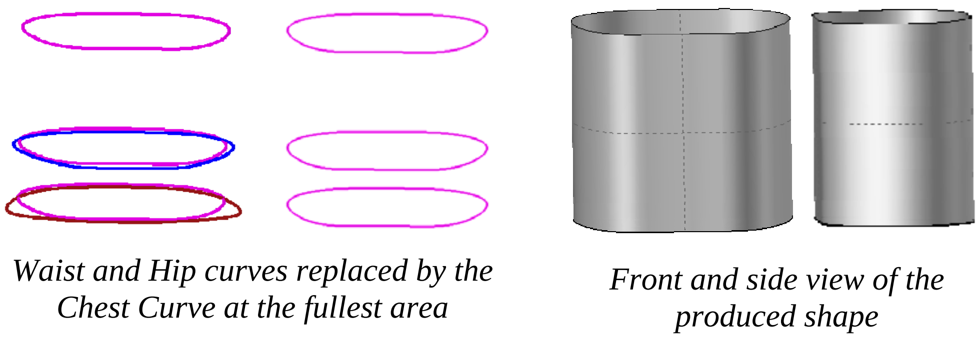


Figure 4-21 Curve Replacement and the produced Shape

For the scaling and final surface generation processes, the duplicated copies of the chest curve were used instead of the waist and hip curves and they will be hereafter described as waist and hip curves due to the locations in which they are used.

4.6 The Scaling Process

As a part of the scaling process, all of the modified and symmetrical body and sleeve curves are defined as length parameters. For each of the curves, an additional parameter is defined to facilitate the acceptance of external values from a size table for the purpose of resizing or grading. Then the subsequent step involves selecting scaling points for each of the curves from which they would enlarge or diminish themselves; it was also necessary to incorporate into the software a scaling factor, so that the program would be able to determine the extent of the enlargement and diminution of each curve during resizing and grading.

The scaling factors for each of the curves are defined as A'/A, where:

A' = the value of a desired size of girth curve; and

A = the existing circumferential value of that girth curve.

The value of the desired size for each curve equates to the size measurement for a particular type of clothing.

4.6.1 Scaling the Body Curves

The middle point of the lines joining the front and back part of each curve (the halving lines in Figure 4-22) were selected as scaling points for all the body girth curves except the hip curve. Designations of two parameters for each of the body curves are listed in Table 4-2. The body curves except the hip curve are scaled only in the horizontal plane (i.e. $\pm$ X and $\pm$ Y axis) with a single factor for each of the curves.

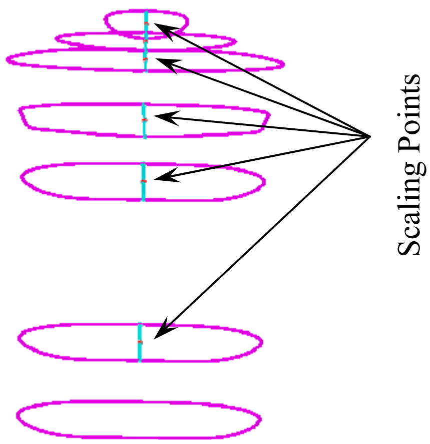


Figure 4-22 Scaling Points for the Body Curves

Table 4-2 Lists of Parameters and Scaling Factors for Body Curves

	Names of The Curves	Parameter Designation for Existing Length	Parameter Designation for External Values from Size Table	Scaling Factor (A'/A)
1	Neck Girth	Ng	Ng_ST	Ng_ST/Ng
2	Lower Neck Girth	LNg	LNg_ST	LNg_ST/LNg
3	Shoulder Girth	Sg	Sg_ST	Sg_ST/Sg
4	Chest Girth at Armpit	Cg_ap	Cg_ap_ST	Cg_ap_ST/Cg_ap
5	Chest Girth at the Fullest Area	Cg	Cg_ST	Cg_ST/Cg
6	Waist Girth	Wg	Wg_ST	Wg_ST/Wg
7	Hip Girth	Hg	Hg_ST	Hg_ST/Hg
8	Centre Length (Shirt Length)	CL	CL_ST	CL_ST/CL

For the neck curve, for example, Ng represents its original length which was 402.72 mm; and Ng_ST represents the value for resizing it, which would be input through an Excel size table. If the value of Ng_ST was 450mm, for example, the scaling factor (A'/A) would be 450/402.72 (=1.12). Using the appropriate scaling tool from the 3D CAD system in use, the neck curve was scaled form the pre-determined point, shown in Figure 4-23, with a factor of Ng_ST/Ng, which was in this case 1.2. However the value of the scaling factor is variable depending on the value of Ng_ST from the size tables.

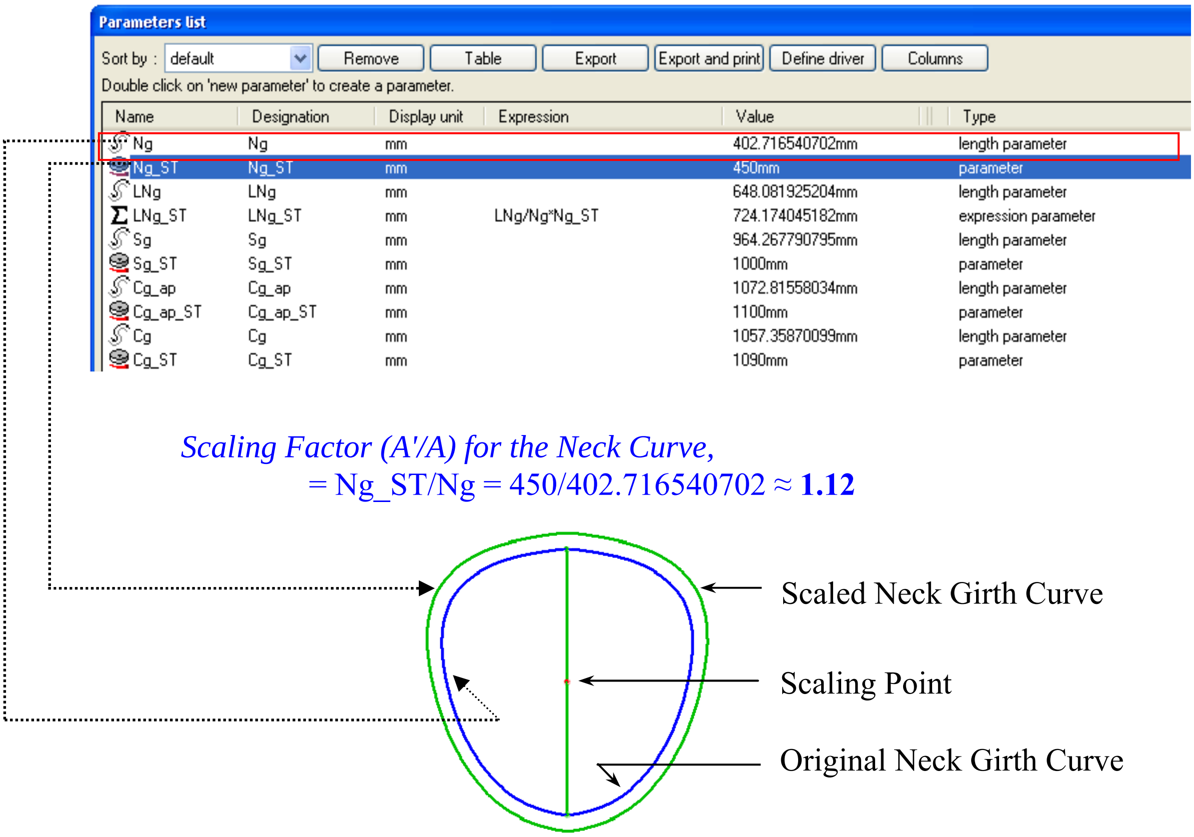


Figure 4-23 Scaling the Neck Curve

Similarly all of the body curves except the hip curve are scaled with their respective factors mentioned in Table 4-2. The hip curve defines the bottom end contour of the proposed shirt template. As the length of the men's shirt can be variable with the size change or within the same size depending on the design, the position of the scaled hip curve should vary in the vertical plane (i.e. according to the change in shirt length). In order to relate the hip curve with the shirt length, the shirt length is first defined as a vertical line from the centre of the neck to hip curve, as shown in Figure 2-24, and scaled with a factor (A'/A) of CL_ST/CL as mentioned in Table 4-2.

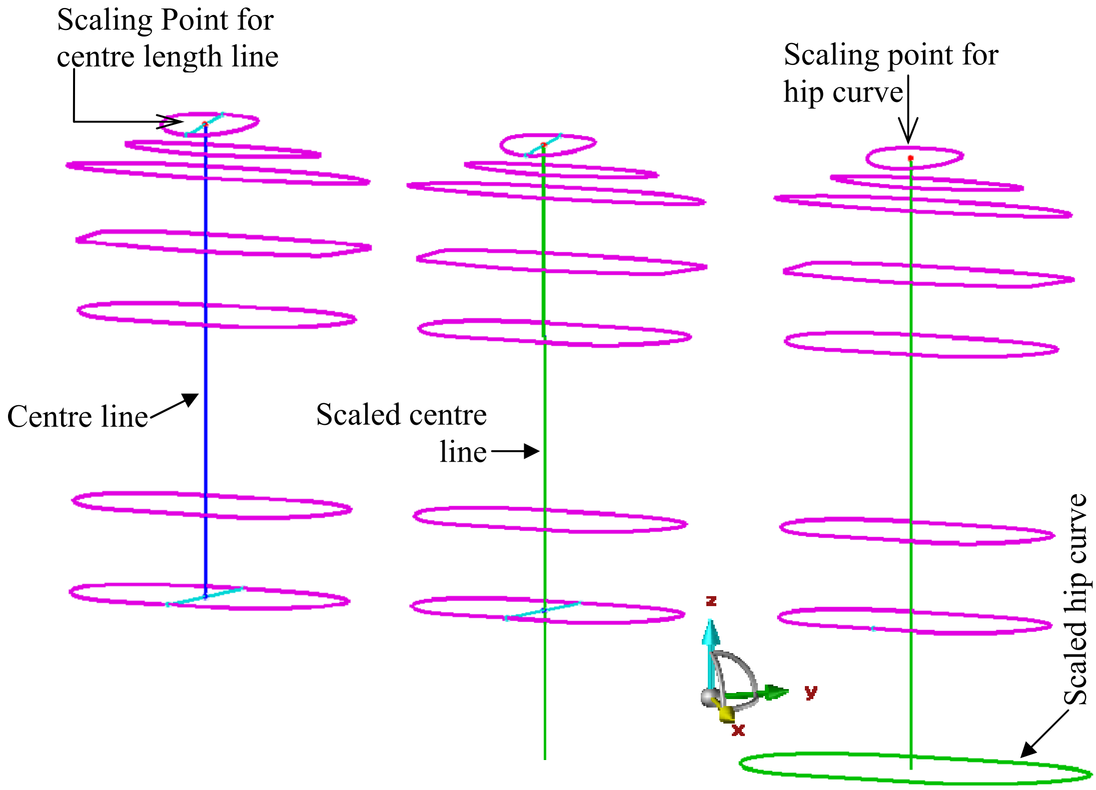


Figure 4-24 Scaling the Hip Curve

Then the hip curve is scaled from the upper end point of the scaled centre length line as shown in Figure 4-24 and with the factor CL_ST/CL for $\pm$Z direction and Hg_ST/Hg for the $\pm$ X and $\pm$ Y directions.

The lower neck curve is essentially used to reproduce the "neck to shoulder" geometry properly. However this is not a standard measurement location from the clothing manufacturing point of view. To reduce the number of parameters in the size table, this girth measurement is not considered as a direct size parameter for the proposed shirt template. Rather it is related to the neck girth using the following expression parameter:

$$LNg\_ST = LNg/Ng * Ng\_ST$$

So the system will calculate the value of LNg_ST (value of lower neck girth for resizing it) based on the value of Ng_ST (value of neck girth from size table) from the size table as a factor of LNg/Ng (i.e. ratio of original length of lower neck girth to original length of neck girth).

4.6.2 Scaling the Sleeve Curves

Designations of two parameters for each of the sleeve curves are listed in Table 4-3. For the upper arm curve and for the curve "TS" representing the upper edge of the sleeve, the middle points of the halving lines joining the front and back parts of the chest girth at the armpit level and the shoulder girth curves respectively, are taken as scaling points (see Figure 4-25).

Table 4-3 Lists of Parameters and Scaling Factors for Sleeve Curves

	Names of The Curves	Parameter Designation for Existing Length	Parameter Designation for External Values from Size Table	Scaling Factor (A'/A)
1	Curve "TS"	Ts	Ts_ST	Ts_ST /Ts
2	Upper Arm Girth	UAg	UAg_ST	UAg_ST /UAg
3	Arm Girth at Bicep	Ag_b	Ag_b_ST	Ag_b_ST /Ag_b
4	Forearm Girth	FAg	FAg_ST	FAg_ST /Fag
5	Wrist Girth	Wrg	Wrg_ST	Wrg_ST /Wrg
6	Sleeve Length	SL	SL_ST	SL_ST/SL

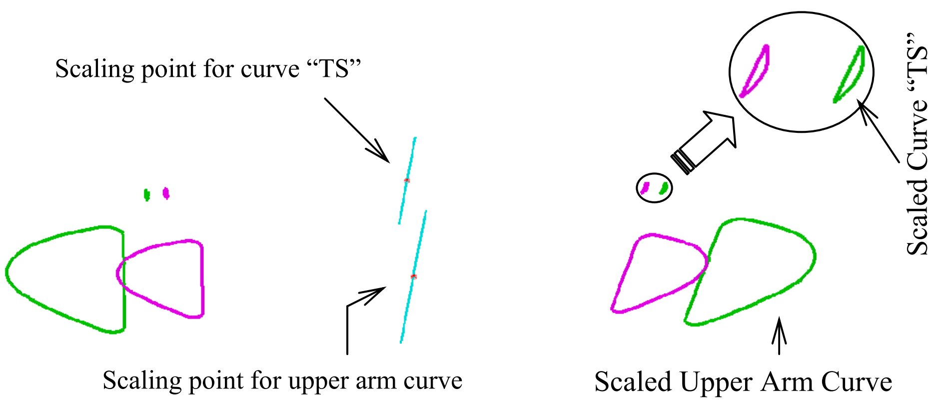


Figure 4-25 Scaling Curve "TS" and Upper Arm Curve

The curve "TS" and the upper arm curve were scaled on the horizontal planes based on the factors mentioned in Table 4-3. Similarly the curves representing arm girth at the bicep and the forearm girth are scaled on the horizontal plane, but the scaling points were taken as the middle points of the lines joining the curves from left and right sleeves, as can be seen in Figure 4-26.

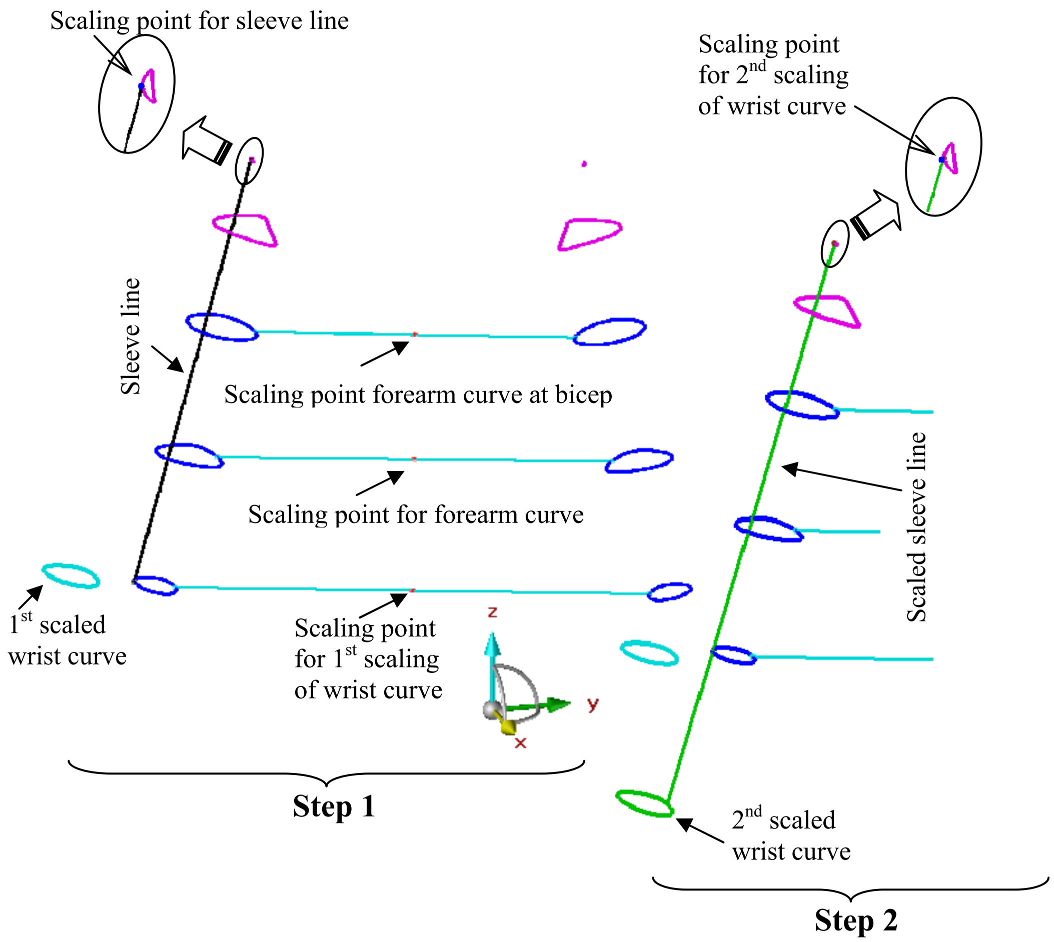


Figure 4-26 Scaling of Wrist Girth Curve

To ensure the change in sleeve length corresponds with the change in clothing size or design, the wrist curve was scaled both on horizontal and vertical planes. The procedure was completed in two steps, which are illustrated in Figure 4-26. At first the wrist curve was scaled on a horizontal plane from the middle point of the line joining the left and right wrist curves. The newly scaled wrist curve was scaled again on a vertical plane based on the end point of the scaled sleeve line as the scaling point, as can be seen on the left side of Figure 4-26. The twice-scaled wrist curve (the 2nd scaled in Figure 4-26) was finally used in the surface generation process described in the next section. As a result, the scaled wrist curve changes its size based on the change of its value in the size table and also changes its position based on the change in sleeve length in the size table.

Similarly to the creation of the lower neck curve described in previous section, the curve "TS" does not represent a standard measurement location from the clothing manufacturing point of view. To reduce the number of parameters in the size table, it is related with the shoulder girth using the following expression parameter:

$$Ts\_ST = Ts/Sg * Sg\_ST$$

So the system will calculate the value of Ts_ST based on the values of the parameters Ts, Sg and Sg_ST, where the value of Sg_ST will be input from size tables and the values of Ts and Sg are presented to the system as length parameters.

4.7 Surface Generation to form the 3D Shirt Template

Once all the body and sleeve curves have been scaled, a geometric modelling technique was applied to generate a new surface out of them, employing the *"curve to curve"* matching and *parametric synchronisation* options within the 3D modelling function of the DCTT software, as illustrated in Figure 4-27. The newly-generated surfaces for the body and sleeves form the desired shirt template as 3D design platform for virtual clothing creation, pattern flattening and automatic grading in 3D as can be seen in the Figure 4-28.

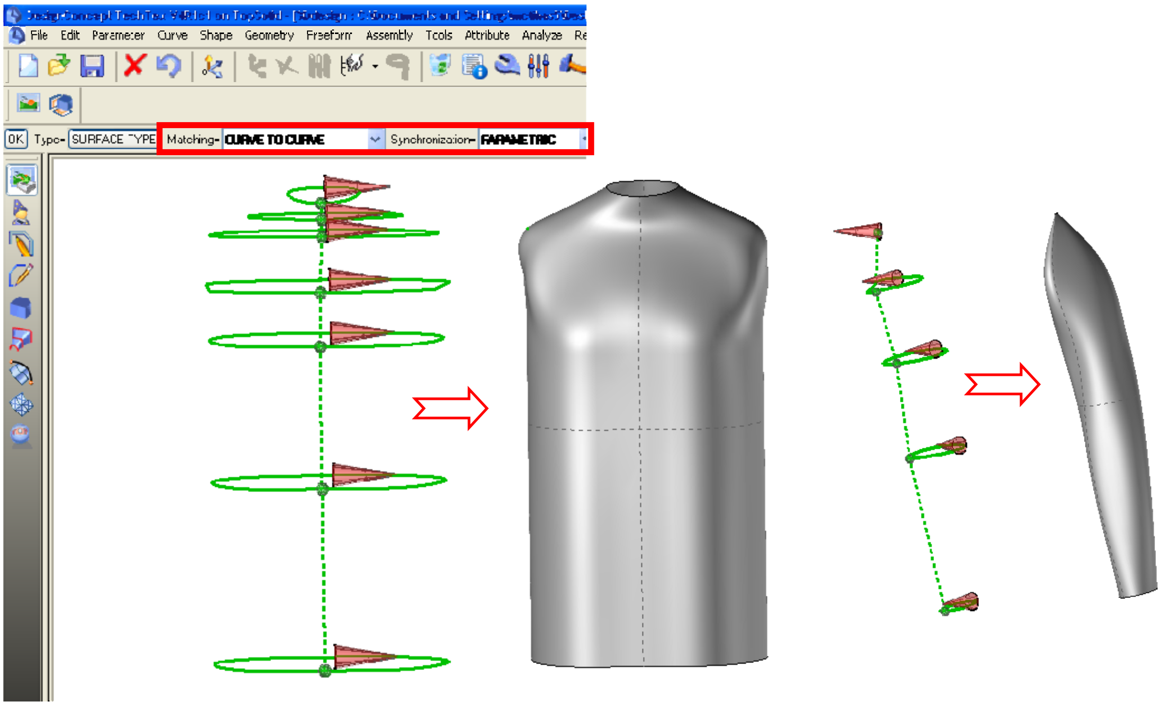


Figure 4-27 New Surface Generation out of Scaled Body and Sleeve Curves

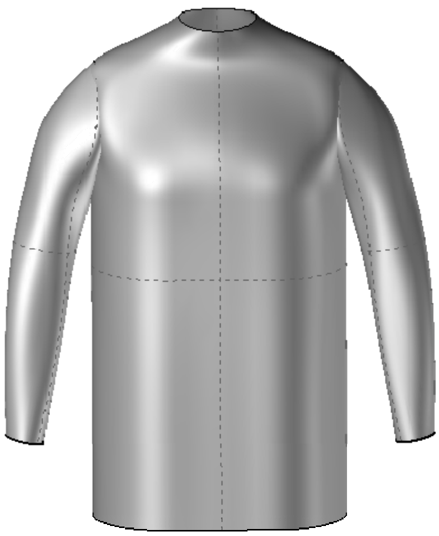


Figure 4-28 The Shirt Template

4.8 Developing Size Databases for 3D Grading

A database of sizes from 37 to 45 for men's shirts has been developed using the MS Excel spreadsheet program, as detailed in Table 4-4. The values for neck girth, chest girths, waist girth, hip girth and wrist girth were taken from the standard body measurements for mature figures of regular males described by Aldrich (1990) in the second edition of the book "Metric Pattern Cutting for Menswear".

The values for the shoulder girth, upper arm girth, arm girth at the bicep and forearm girth are not available in any traditional size tables. The following method has been used to derive the values of these girth curves, initially for size 42, which were subsequently graded accordingly for other sizes from 37 to 45 as may be seen in Tables 4-4 and 4-5.

- For the shoulder girth, upper arm girth, arm girth at the bicep and forearm girth, the measurements extracted from the scan data, which has been used throughout this work, were selected for use in the size table as the measurement for size 42, because the subject from which the scan data were generated and from which the subsequent body model was developed had chest measurement and waist measurement close to that described by Aldrich (1990) for this size.

The size table was split into sub-databases for individual sizes with appropriate ease allowances. A minimum functional ease of 7.5 cm for the chest area was selected following the findings of Moll and Wright (1972) and a design ease of 8.5 cm was selected to make a total ease of 16 cm which corresponds to the suggested ease around the chest (without a seam allowance) for easy-fitting men's tee shirts and knitwear, by Aldrich (1990).

When creating a straight side-seam silhouette for a man's shirt, sufficient ease allowances for the waist girth and hip girth were selected to keep the final measurements equal across the chest area. Although no circumferential expansion takes place in the arms as it does for the chest and waist areas due to the breathing mechanism, sufficient functional ease is required in the sleeves to allow for unhampered arm movement. The size parameters with ease allowances for size 42 are included in Table 4-5. The same ease allowances have been included for other sizes, namely 37, 38, 39, 40, 41, 43, 44 and 45 and are reproduced in Appendix 4.

Table 4-4 Size Table for Men's Tee-Shirt

	Size Parameter	Measurements for Men's Shirts (without ease) in cm (***neck size as size designation***)								
		37	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**
1	Neck Girth	37	38	39	40	41	42	43	44	45
2	Shoulder Girth	87	89	91	93	95	97	99	101	103
3	Chest girth at armpit	88	92	96	100	104	108	112	116	120
4	Chest girth at the fullest area	88	92	96	100	104	108	112	116	120
5	Waist girth	74	78	82	86	90	98	102	106	110
6	Hip girth	92	96	100	104	108	114	118	122	126
7	Upper arm girth	30	31	32	33	34	35	36	37	38
8	Arm girth on bicep	29.5	30.5	31.5	32.5	33.5	34.5	35.5	36.5	37.5
9	Forearm girth	27	28	29	30	31	32	33	34	35
10	Wrist girth	22	22.5	22.5	23	23	23.5	23.5	24	24
11	Shirt Length	76	78	80	81	81	82	82	82	82
12	Long Sleeve Length	87	88	88	89	89	90	90	90	90

Table 4-5 Size Parameters with Ease Allowance for Size 42

Size Parameter	**Measurement without ease (cm)**	**Functional Ease (cm)**	**Design Ease (cm)**	**Clothing measurement (cm)**
Neck Girth	42	0	0	42
Shoulder Girth	97	0	1	98
Chest girth at armpit	108	7.5	8.5	124
Chest girth at the fullest area	108	7.5	8.5	124
Waist girth	98	7.5	18.5	124
Hip girth	114	0	10	124
Upper arm girth	34	7	0	41
Arm girth on bicep	33	6.5	0	39.5
Forearm girth	30.5	4.5	0	35
Wrist girth	23.5	2	0	25.5
Shirt Length	82	-	-	82
Long Sleeve Length	90	-	-	90

Once all the size tables with ease allowances had been prepared in Excel spreadsheets, they were programmed, by assigning parameters designations to the corresponding cells containing size parameters, to be linked with the 3D grading process using the "*Excel link*" facility within the DCTT software suite.

4.9 Testing the Shirt Template

4.9.1 Drawing Platform and Virtual Clothing

In order to check the functionality of the shirt template as a 3D drawing and design platform, different free-hand curves and outlines of different shirt designs were drawn on this shirt template. Figure 4-29 shows the drawn outline of a long-sleeve shirt. As the template is a model of the upper body surface to which operational levels of ease have been appended, drawing on the template effectively defines the 3D outlines of an appropriately-sized garment. Once a drawing has been completed, an area of triangulated mesh is created on the template using the *"create region"* tool within the DCTT software. Figure 4-30 shows the triangulated form along with the region creation dialog box. This triangulated shape thus forms the virtual clothing.

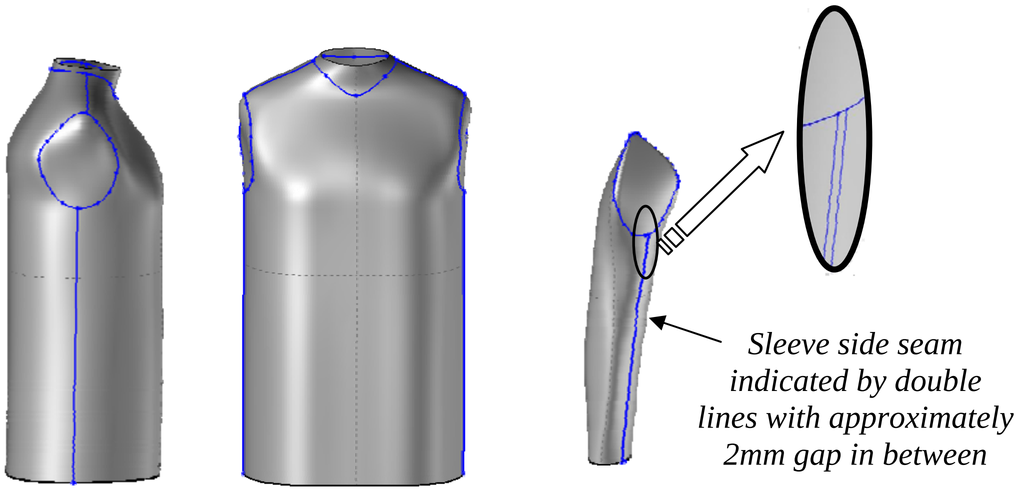


Figure 4-29 Drawing Shirt Outline on the Shirt Template

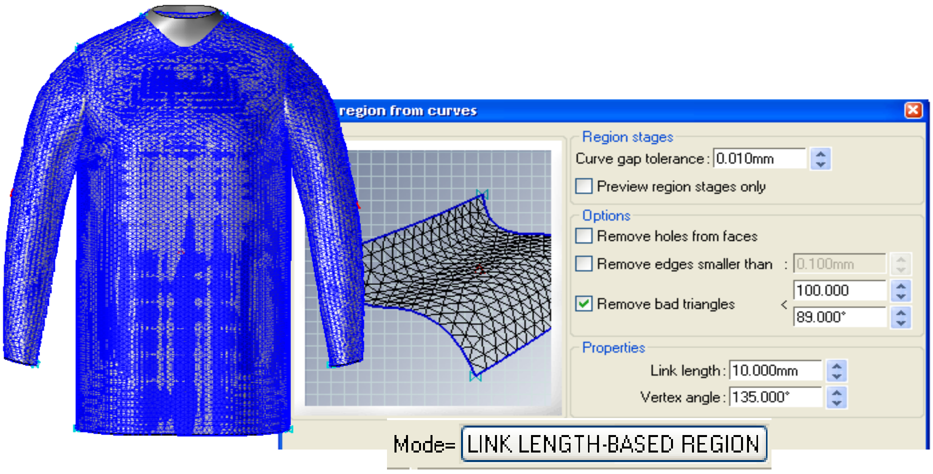


Figure 4-30 Triangulated 3D Mesh Structure based on drawn Outline

Similarly, designs of short sleeve shirt and other upper body men's outerwear were developed on the 3D shirt template to check its functionality.

During the "link-length based" region creation, different combinations of link length and vertex angle were tried to check their effect on the mesh quality and on the ultimate pattern flattening process.

4.9.2 Resizability and Automatic Grading

The resizability of the shirt template was checked by individually varying the values of different size parameters; the changes in the size and position of the scaled curves and the corresponding shape of the body and sleeves were observed. Figure 4-31 shows the changes in the length of the shirt template when the value of the parameter of shirt's centre length (CL_ST) is manually altered from 63cm to 82cm keeping all other measurements unchanged.

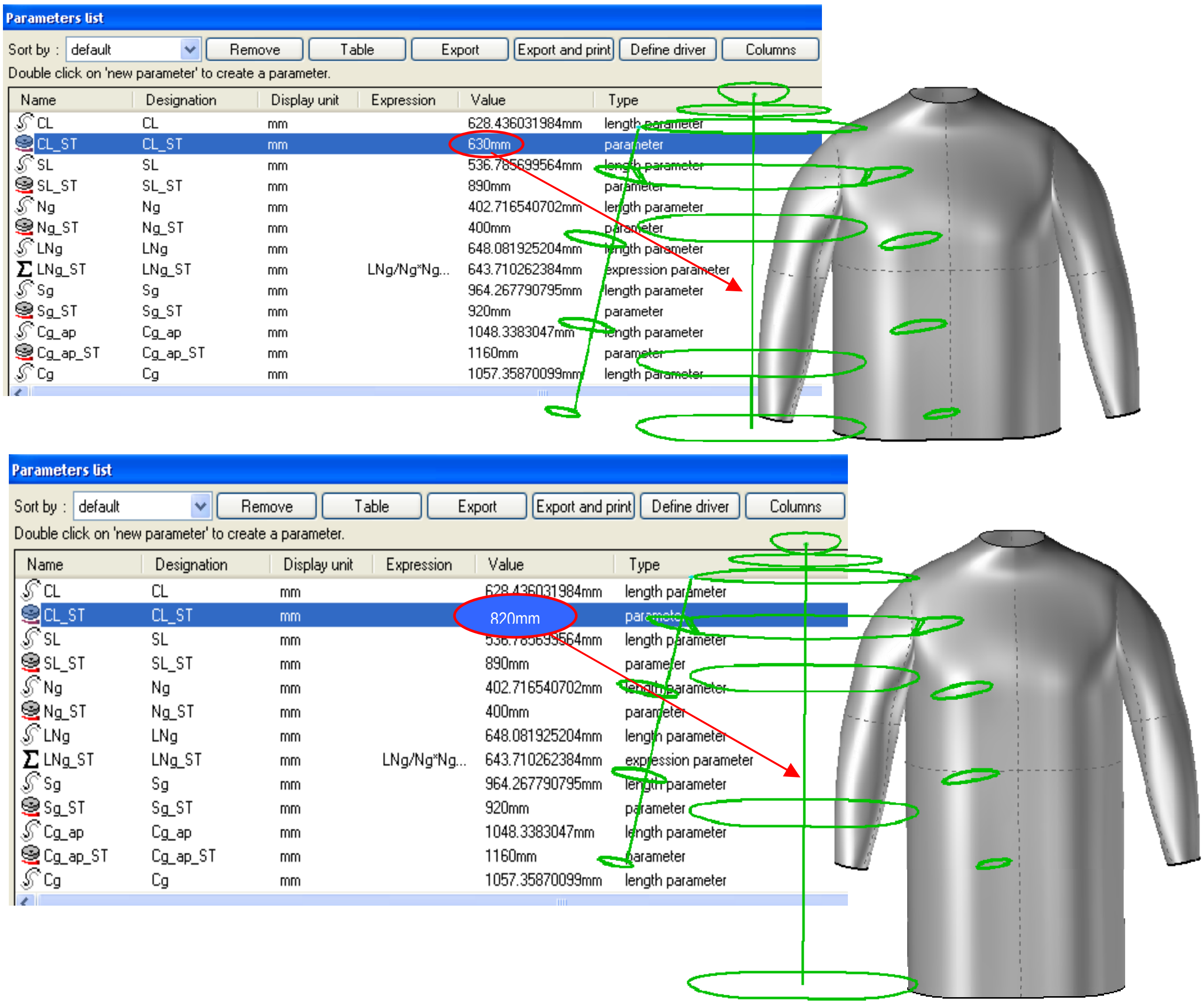


Figure 4-31 Effect of Changing the Shirt Length only

To check the resizability of all of the scaled curves together as a group and to assess the capability for grading of virtual clothing in space, the pre-developed size databases were linked with the 3D shirt template using the "*Excel link*" facility available within the DCTT software suite. The changes in size and shape of the shirt template, as well as the virtual shirt drawn on it, were assessed.

4.9.3 Pattern Flattening and Physical Prototype

The available flattening tools provided within the DCTT software suit were used to unwrap the virtual clothing designed on the shirt template, part by part, following the clothing manufacturing process. Figure 4-32 illustrates the flattening process of the front part of the 3D tee-shirt design developed on the shirt template. By selecting the "match edge-lengths" option during flattening, dimensional integrity of the flat pattern pieces with the 3D design could be maintained. Similarly the back part and the sleeves were also flattened into 2D pattern pieces.

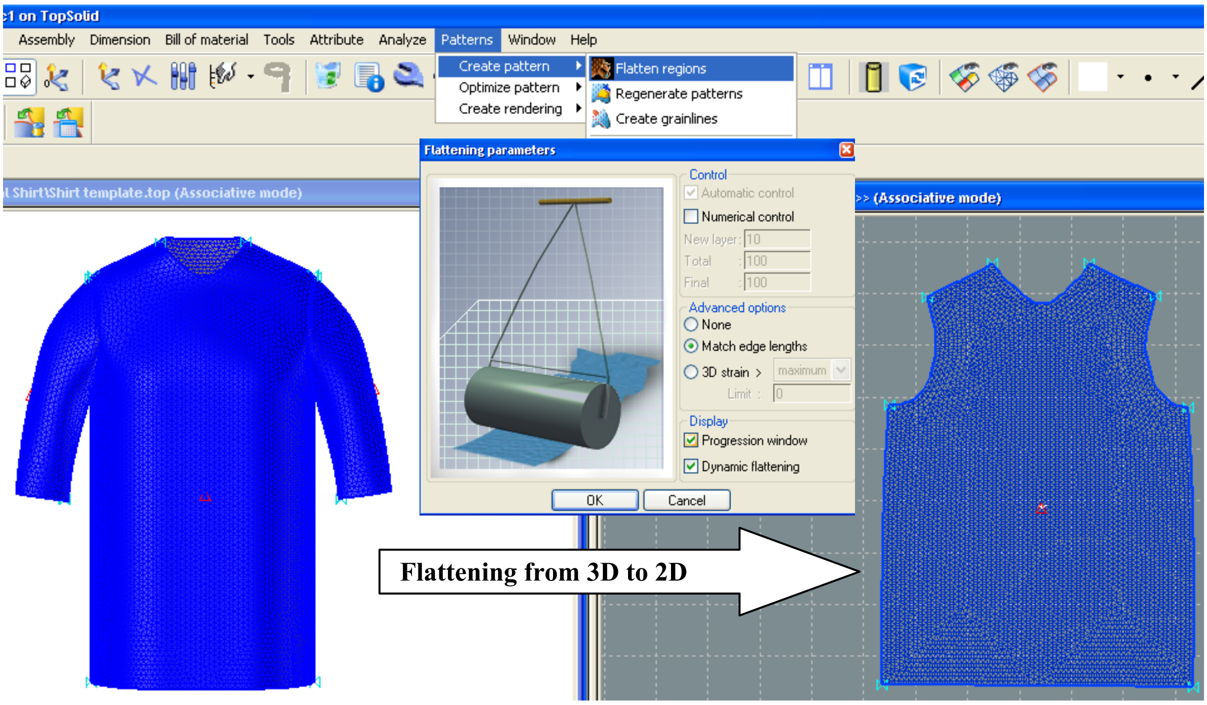
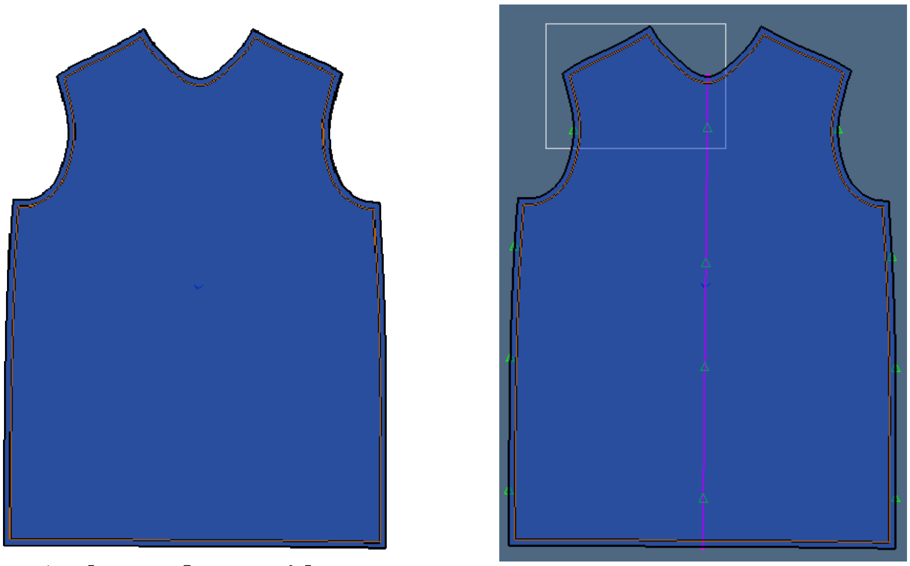


Figure 4-32 Flattening 3D Parts into 2D Pattern

The virtual shirt designs were graded into different sizes and flat pattern pieces were derived from them. Measurements of the all edges of flattened pattern pieces were compared with those of the 3D design.

A 1 cm seam allowance was added to the flattened pattern pieces of size 38 and size 40 before printing them for the purpose of physical prototyping. As there was no plotter available to print a full size pattern, each of the pattern pieces was split into several A4 size sheets. On each pattern piece, a centre line was drawn; the boundary lines and the drawn centre line were then marked at different places before printing them on A4 size paper, as can be seen in Figure 4-33. After printing the parts of each pattern piece were manually joined together with the help of the marks.



A) Flattened Part with Seam Allowance

B) Pattern Preparation for Printing on A4 Size Papers

Figure 4-33 Flattened Front Part of the 3D Tee-shirt

Figure 4-34 Physical Prototypes of Men's Short-sleeved Tee-shirts

Two physical prototypes of men’s short-sleeved tee-shirts (Figure 4-34) one in size 38 and another in size 40 were prepared. They were made of 100% cotton single jersey knitted fabric of 180 g/m^2 based on the printed pattern pieces. Manufacturing specifications of the tee-shirt prototypes are presented in Tables 4-6 and 4-7. The seam classes, stitch classes and their illustrations are presented in the tables according to the British standards BS 3870-1: 1991 (ISO 4915:1991) and BS 3870-2: 1991 (ISO 4916:1991)

Table 4-6 Specifications of the Tee-shirt made in Size 38

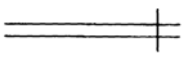
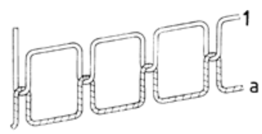
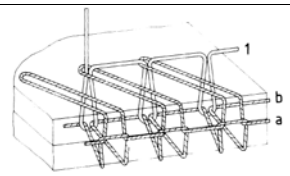
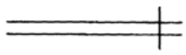
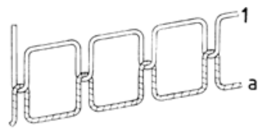
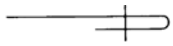
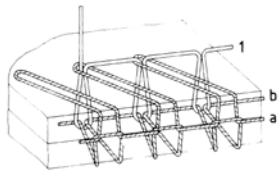
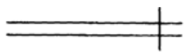
<table>
<tr><th></th><th>Seam/Joining Area</th><th>Seam Class</th><th>Seam Illustration</th><th>Stitch Type and Class</th><th>Stitch Illustration</th></tr>
<tr><td>1</td><td>Shoulder Seams</td><td rowspan="3">1.01.01</td><td rowspan="3"></td><td rowspan="3">Lock Stitch (301)</td><td rowspan="3">1= Needle thread, a= Bobbin thread</td></tr>
<tr><td>2</td><td>Sleeve and Body joints at Armholes</td></tr>
<tr><td>3</td><td>Side seams</td></tr>
<tr><td>4</td><td>Sleeve opening</td><td rowspan="2">6.01.01</td><td rowspan="2"></td><td rowspan="2">Overedge Chain Stitch (504)</td><td rowspan="2">1=Needle thread, a & b = Looper threads</td></tr>
<tr><td>5</td><td>Bottom opening</td></tr>
</table>

Table 4-7 Specifications of the Tee-shirt made in size 40

	Seam/Joining Area	Seam Class	Seam Illustration	Stitch Type and Class	Stitch Illustration
1	Sleeve and Body joints at Armholes	1.01.01		Lock Stitch (301)	 1= Needle thread, a= Bobbin thread
2	Side seams				
3	Neck	6.02.03		Lock Stitch (301)	
4	Bottom opening				
5	Sleeve opening	6.01.01		Overedge Chain Stitch (504)	 1=Needle thread, a & b = Looper threads
6	Shoulder Seams	1.01.01			

Trials of the physical prototypes were arranged with live models to check the general fit quality and to assess the usability of the flattened pattern pieces derived from the 3D shirt template, which has been described from section 4.1 to 4.7.

4.9.4 Fashion Visualisation in 3D

Virtual shirts developed on the design platform were rendered with different graphical surfaces, as for example is shown in Figures 4-35 and 4-36, using the existing design capability of the software to assess the possibility of executing clothing design and fashion visualisation in a 3D format. Figure 4-35 shows an example of using an available rendering mode to visualise the triangulated mesh surface as a solid surface.

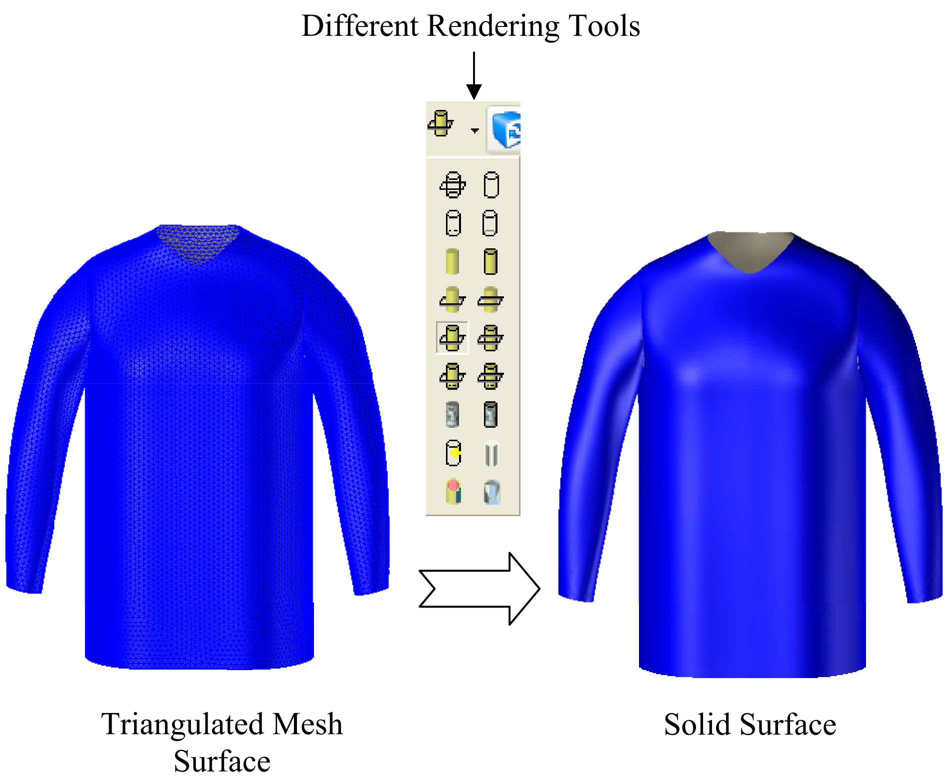


Figure 4-35 Applying Different Rendering Tools on Virtual Shirt

Figure 4-36 shows the example of producing a stripe effect using image data. The image of the Manchester University logo has been used as a repeat to create the stripe effects both in the horizontal and vertical directions. This was done using the "create rendering" tool from the "pattern" menu, when the 2D pattern window was active.

Similarly different graphical surfaces were applied to the virtual shirt prototypes to exploit the fashion illustration in 3D format.

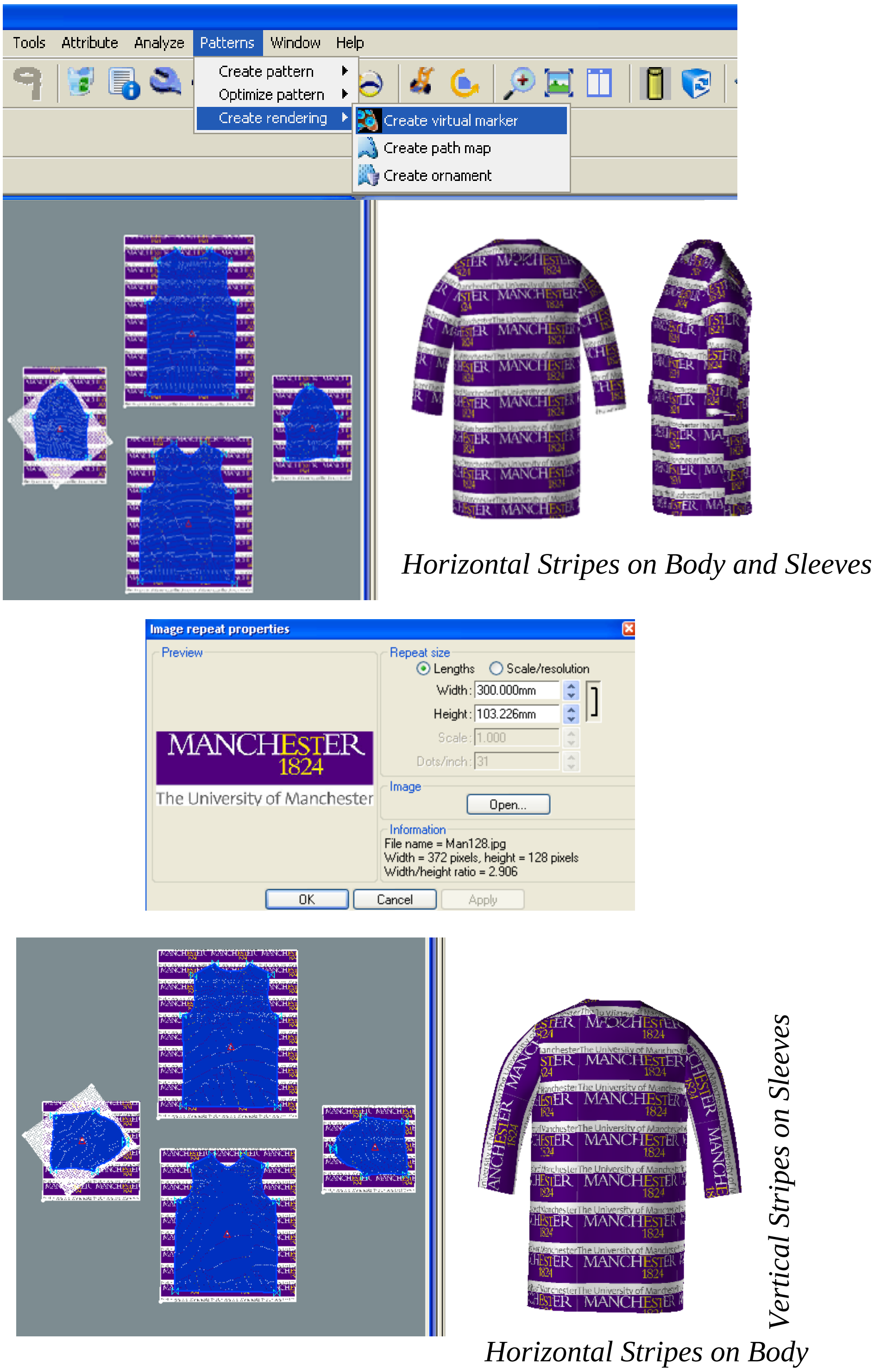


Figure 4-36 Stripe Effects using an External Image

Chapter 5: Resizable Trousers Template

5.1 Work Flow

The process followed to develop a resizable trousers template is summarised in Figure 5-1.

Body scanning

⇩

Generate CAD model from Point-Cloud

⇩

Slice the CAD model to extract sectional curves from waist to feet area of body

⇩

Select one half of the extracted curves and generate B-Splines

⇩

Scale the B-Splines

⇩

Generate new surface from the scaled curves to develop half of the "Resizable Trousers Template"

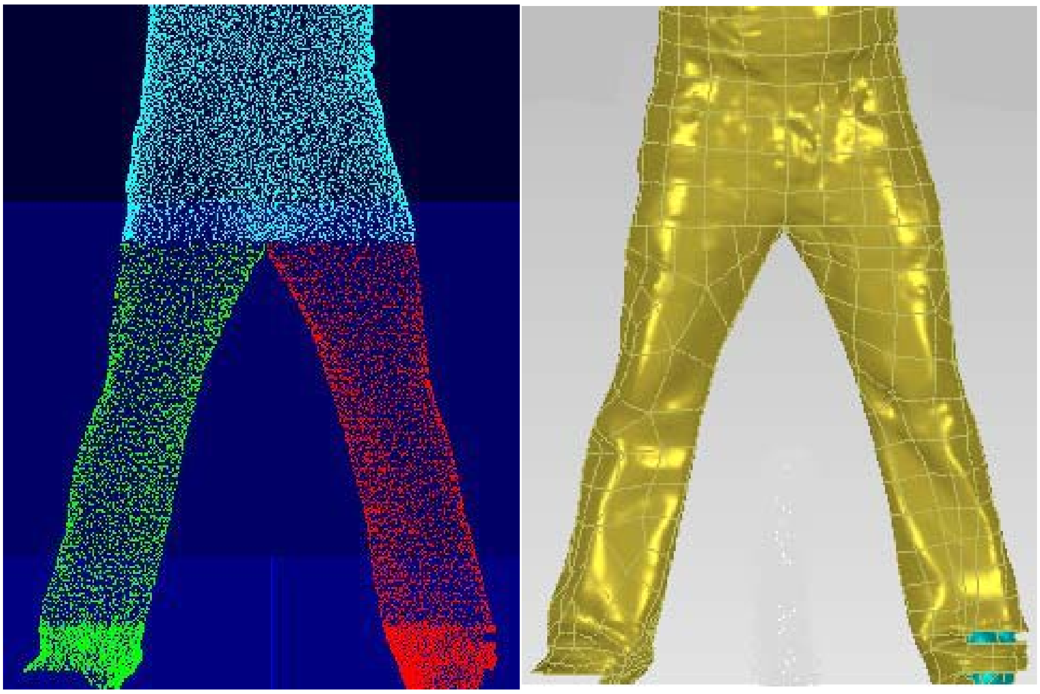
⇩

Duplicate the half template as "mirror image" to the opposite side to a create symmetrical "Resizable Trousers Template"

Figure 5-1 Workflow for Resizable Trousers Template

5.2 Reverse Engineering

A male subject of 35 years of age, wearing light-coloured casual trousers made of thick woven fabric was scanned using the [TC]² NX-16 3D body-scanning system. The scanner was first calibrated according to the guideline provided by [TC]². The "auto-scan" option was followed to capture Point Cloud data, which was processed into a triangulated body model as an ".obj" file format using the NX16 proprietary software. This triangulated body model was further processed in the RE software "Geomagic Studio" to generate a CAD model, as can be seen in Figure 5-2.



Scan data **CAD Model**

Figure 5-2 Scan Data and CAD Model

The male subject was also scanned without trousers, but wearing underwear, so that the body measurements might be extracted. Table 5-1 lists the relevant measurements extracted from the body scan data.

Table 5-1 Relevant Measurements extracted from Body scan Data

Measurement Positions	Measurement in cm	
	With Trousers	Without Trousers
Waist	93.1	92.7
Low waist (4cm below waist)	97.1	97
Seat	103.8	104
Upper thigh as crotch point (UTCP)	65.1	62.2
Thigh (4cm below UTCP)	58.4	53.3
Knee	46	40
Girth at hem	46	26

5.3 Extraction of Sectional Curves

Nine sectional curves as shown in Figure 5-3 were extracted by slicing the CAD model at the pre-selected girth measurement locations that have been found to best represent the shape and size of casual trousers. These girth measurement locations are: the waist, the low waist, seat, looseness control girth 1 (LCG1), looseness control girth 2 (LCG2), upper thigh girths taken at the crotch point (UTCP), thigh, knee and at the hem at the end of each leg.

The Waist position was located using the smallest girth measurement through the horizontal plane, according to the European Standard for size designation of clothes "EN 13402-2001". The positions of the low waist and seat are not suggested in this standard. According to Aldrich (1990), the low waist measurement may be taken 4 cm below the waistline. The pictorial definitions of the seat provided by Aldrich (1990) and Cooklin (1992) with the help of a front and back view of a male body are not technically very clear. According to the [TC]² software tutorial, "*the seat is a fixed circumference measurement taken as horizontal slice at the height where the buttocks protrude most to the rear*" (see figure 5-4) . This definition provides a clear guideline for identifying the seat location on a virtual body.

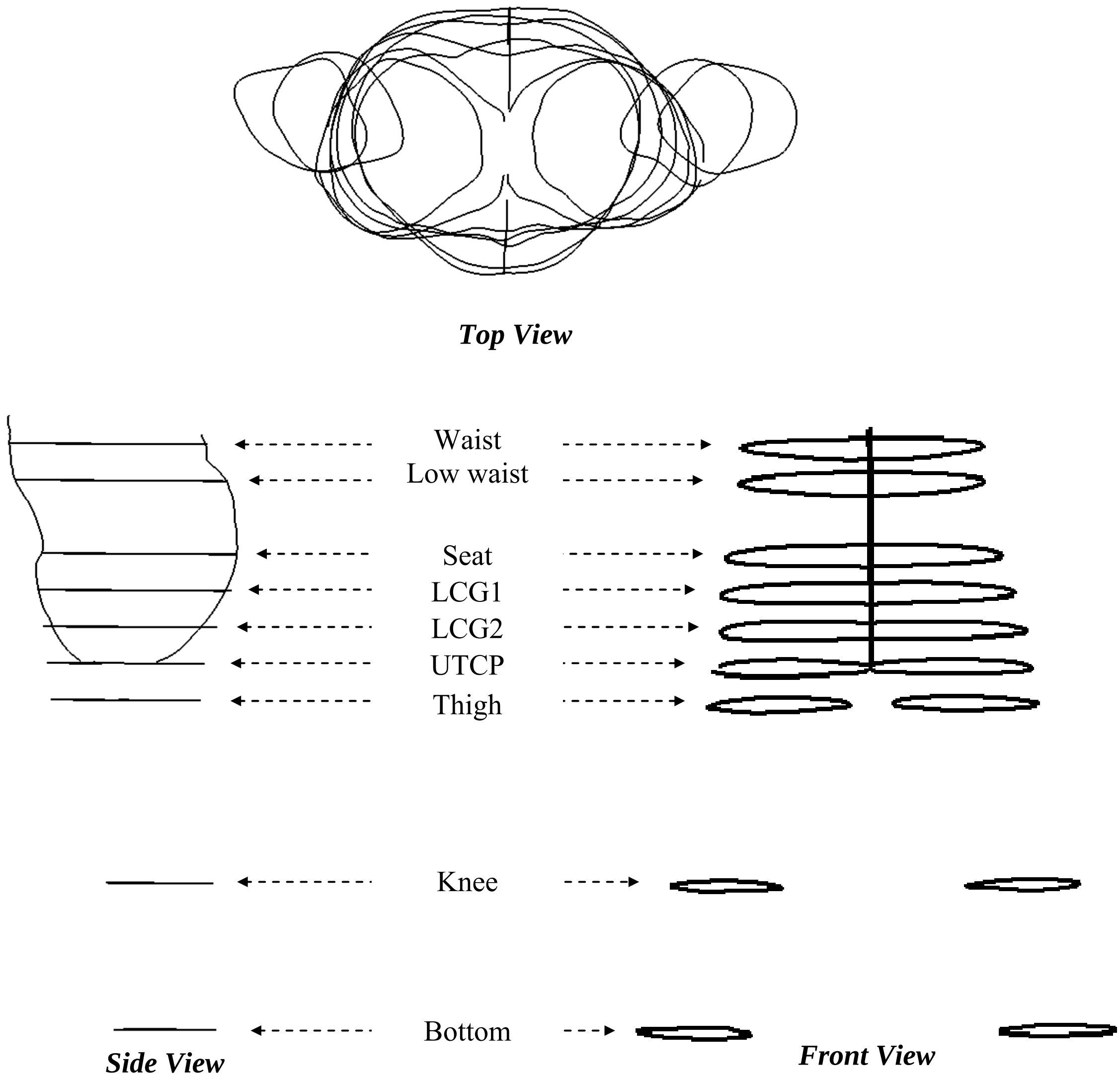


Figure 5-3 Sectional Curves Extracted from the CAD Model

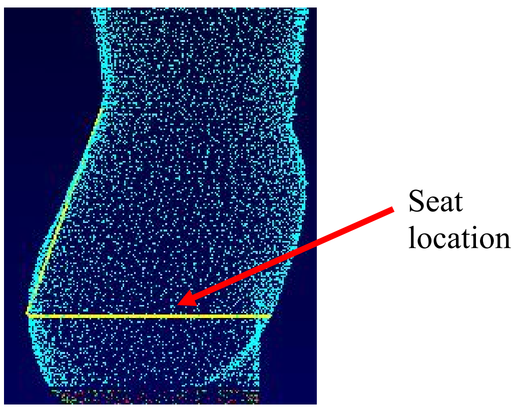


Figure 5-4 Location of Seat (TC² Tutorial 2, n.d.)

The Looseness Control Girth 1 and 2 (LCG 1 & 2) were located between the Seat and Crotch. These two girths together with the upper thigh girths taken at the crotch point (UTCP) and the thigh girths (taken 4 cm below the UTCP) are responsible for giving a variable silhouette and looseness to trousers. The waist and seat curves provide suspension for the garment, from which it can hang downwards under gravity.

The sectional curves were imported into the DCTT 3D CAD system that includes tools for 3D modelling and texture mapping, lines and curve drawing, mesh generation from drawn curves and facilitates flattening the 3D surface into 2D.

5.4 Generation of Modified Curves

It was found that the curves that were generated by the extraction process were discontinuous and they were also insufficiently smooth along their contours to be used as high quality templates upon which to create garments. Hence, a set of revised curves was created over the extracted curves using the B-spline curve-drawing tool. By removing small imperfections such as short concave and convex sections along each of the contours, a uniform surface was created for the proposed template. An overhead view of the original thigh curve can be seen in Figure 5-5, with a newly-created B-spline curve drawn over it. The modified thigh curve illustrates the improvement which results when the minor flaws have been smoothed out. The newly-created B-spline curves were used as the basis for scaling up and down to make larger and smaller sizes and as the foundation for surface generation. To ensure a symmetrical finish to the proposed 3D template, a mirror image of one half of the extracted curves was used to form the opposite (matching) half.

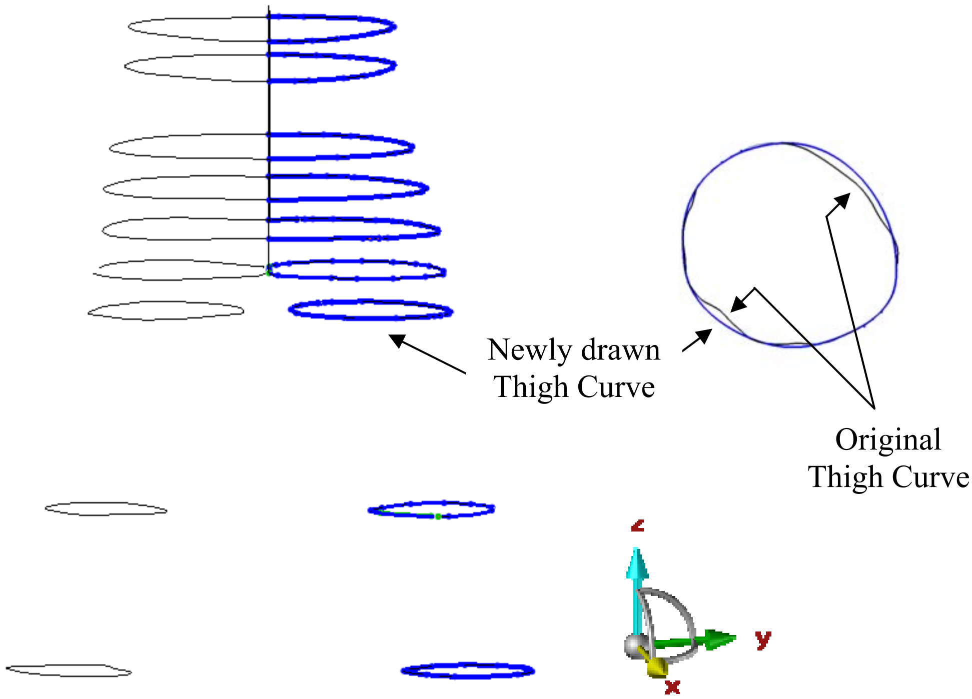


Figure 5-5 Drawing B-Spline Curves on One Half

5.5 Scaling the B-Spline Curves

To facilitate the scaling function, the adapted B-spline curves were divided into three groups: those curves associated with the body rise, those curves associated with the inseam and neutral curves which were not connected with either. The upper thigh girth as measured at the crotch point (UTCP) was categorised as a neutral curve, as in order to scale it up or down, it was required to increase and decrease in size only in respect of the horizontal plane; the X and Y directions of the 3D coordination system. This is clearly unaffected by variations in either the body rise or in respect of the inseam.

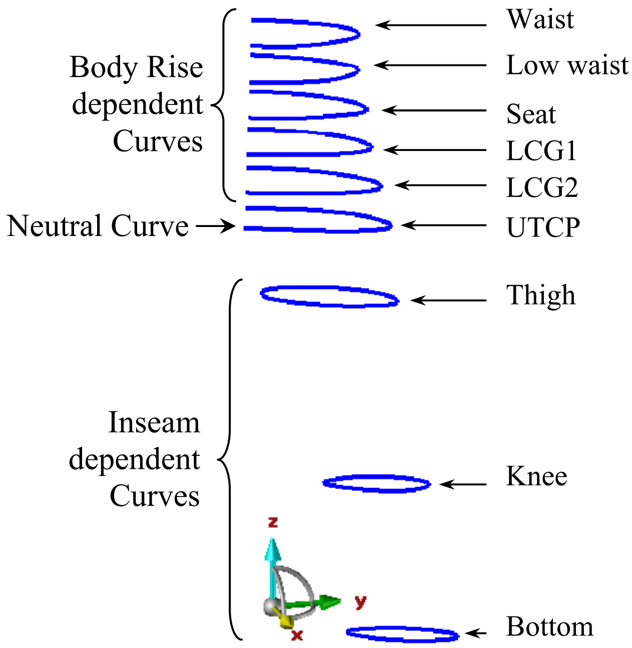


Figure 5-6 Division of Curves for Scaling

The curves for the waist, the low waist, the seat and both LCG 1 and LCG 2 have all been considered to be associated with the body rise, as they are required to change in size in the horizontal plane when the body rise changes, or as a result of the scaling process, which causes their vertical displacements to be varied in either the +Z or the –Z directions respectively as the body rise is either increased or decreased.

The thigh, knee and bottom hem curves were considered to be associated with the inseam, as they subject to vertical displacement of their position in either the +Z or the –Z direction if the inseam is increased or decreased respectively; they are hence required to change in size in the horizontal plane as a direct consequence of scaling.

55.1 Definition of Parameters

Two parameters were defined for each of the curves, one was for the existing length of the curves and another was for the external values from a size table for the purpose of resizing. A scaling factor was defined as a ratio of the two parameters for each of the curves. Table 5-1 lists the parameter designations and the scaling factors for each of the curves.

Table 5-2 Lists of Parameters and Scaling Factors for Trouser Curves

	Names of The Curves	Parameter Designation for Existing Length	Parameter Designation for External Values from Measurement Chart	Scaling Factor (A'/A)
1	Waist	hWG	hWG_m	hWG_m/ hWG
2	Low waist	hLW	hLW_m	hLW_m/ hLW
3	Seat	hSG	hSG_m	hSG_m/ hSG
4	Looseness control girth 1	aG1	aG1_m	aG1_m/aG1
5	Looseness control girth 2	aG2	aG2_m	aG2_m/aG2
6	Body rise	BR	BR_m	BR_m/ BR
7	Inseam length	IL	IL_m	IL_m/ IL
8	Upper thigh at crotch point	UTG_cp	UTG_cp_m	UTG_cp_m/ UTG_cp
9	Thigh	TG	TG_m	TG_m/ TG
10	Knee	KG	KG_m	KG_m/ KG
11	Leg girth at hem (Leg Opening)	BO	BO_m	BO_m/ BO

5.5.2 Scaling the Neutral Curve

The neutral curve was scaled using a single factor which was based on the scaling point shown in Figure 5-6. As shown in Table 5-2, the scaling factor in this case is UTG_cp_m/ UTG_cp.

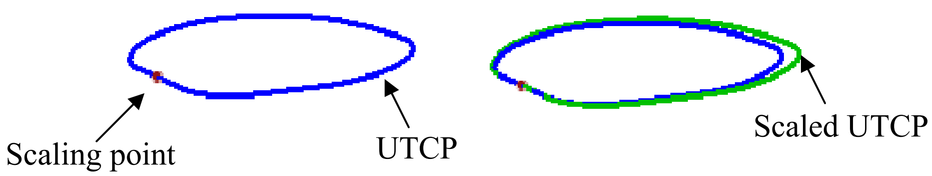


Figure 5-7 Scaling the Neutral Curve

5.5.3 Scaling the Rise-dependent Curves

The rationale behind the scaling of rise-dependent curves is to ensure that the girths of these curves change appropriately in the ±X and ±Y directions when new size measurements are used with the system; this occurs at the same time as the underlying scaling of the vertical displacement in the ±Z direction with a change in body rise length. According to the prevailing sizing system for trousers and shorts, for each step change in garment size, there are incremental changes in the measurements of both the body rise and of the girths in the region between the waist and the crotch. The overall consequence of this is that the anatomical volume and the body measurements from the waist line to the crotch change in both the horizontal and vertical planes with any change of garment size. To ensure that this is reflected in the 3D body model, the body rise was first defined as a vertical line from the centre of the waist to the crotch, as shown in Figure 5-8 and this was scaled from the centre of the waist with a factor of BR_m/BR, where:

BR_m = desired value of the body rise from the size table; and
BR = the existing length of the body rise.

To couple the location and the shape of body rise-dependent curves with any variation in the body rise measurement, they were scaled from the end point of the scaled rise, as indicated in Figure 5-8, using a multi-directional scaling procedure. Changes in their positions in the vertical direction are related to the change in length of the body rise curve. That is why the end point of a scaled rise curve (which changes its location with any change of its length), was taken as a scaling point for all the rise-dependent curves. For scaling in the vertical plane (i.e. in the ±Z direction), the scaling factor of BR_m/BR, which is equivalent to the scaling factor of the rise curve, was used to determine the appropriate vertical displacement of any position, which is related to the length of the body rise.

And for the horizontal plane (i.e. in the ±X and ±Y directions), the relevant scaling factor used for each of the curves was that described in Table 5-2.

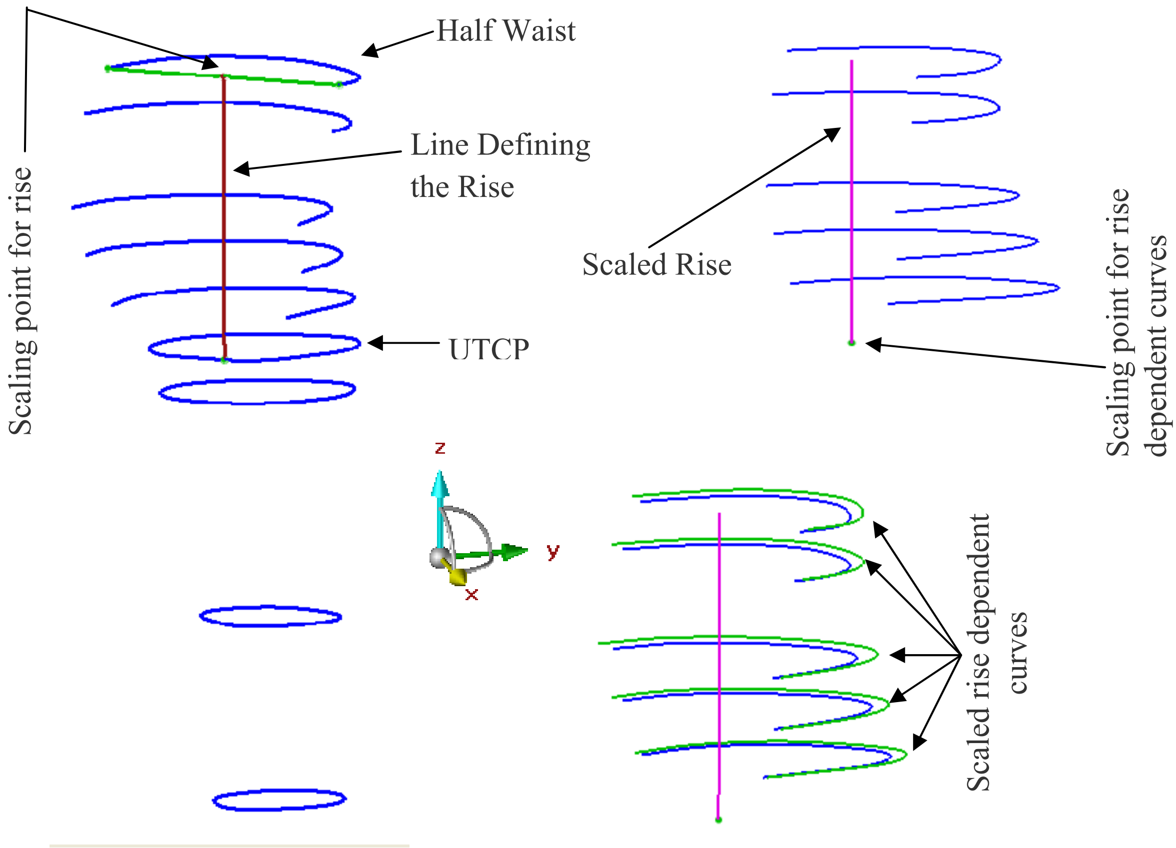


Figure 5-8 Scaling Rise Dependent Curves

5.5.4 Scaling the Inseam-dependent Curves

In analogous fashion to the scaling of all the body-rise related measurements, the inseam-dependent curves also needed to be scaled in multiple directions with appropriate factors being incorporated to accurately define the size changes in the ±X and ±Y directions and the vertical displacement in the ±Z direction, in relation to any changes of the inseam length. Prior to implementation of any scaling factors, the inseam line was defined as joining the innermost points of the curves as illustrated in Figure 5-9 and was scaled from its upper end with a factor of IL_m/IL, where:

IL_m = desired length of the inseam from the size table; and

IL = the existing length of the inseam.

The inseam dependent curves were thus scaled from the upper end point of the scaled inseam line, as shown in Figure 5-9, with the factor IL_m/IL for the +Z direction and with the pertinent factors from Table 5-2 being used for the +X and +Y directions.

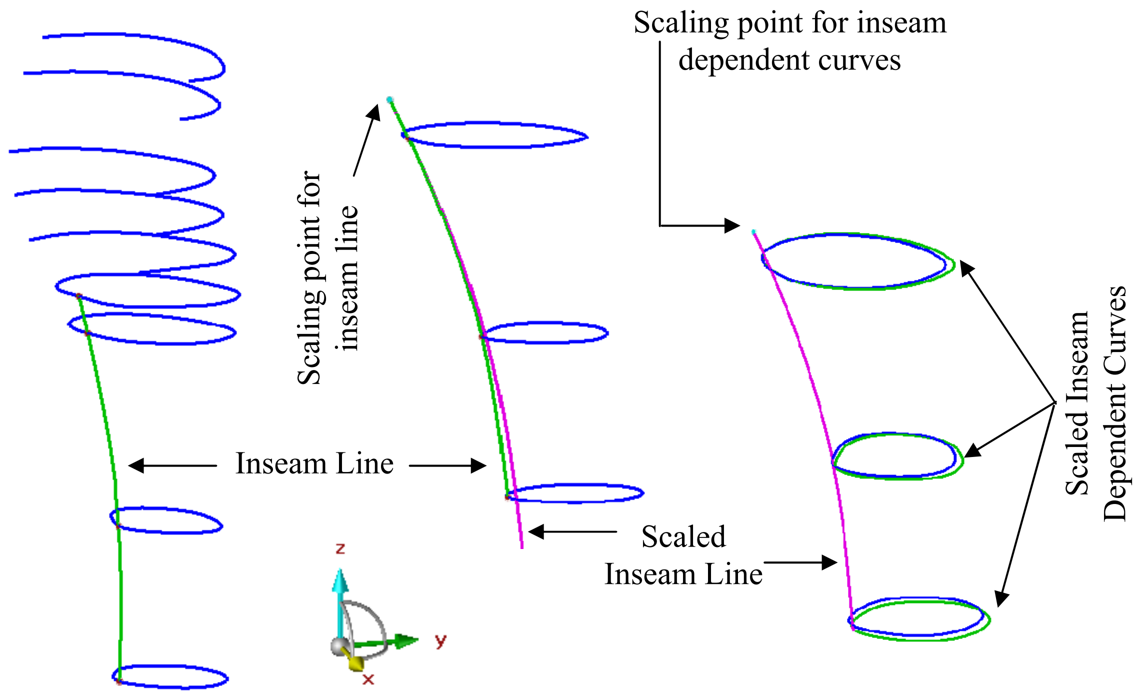


Figure 5-9 Scaling the Inseam-dependent Curves

5.6 New Surface Generation

When all the nine curves used to define the various girths of the 3D virtual model had been scaled according to the required size and linked with appropriate figures in the size databases, a geometric modelling technique was invoked to generate a new surface using this information. It was intended to generate the new surface by following the geometry of the scaled curves that were representative of the appropriate size parameters. To implement this, a "*curve to curve matching*" option was selected and the "*parametric synchronisation*" option was employed to ensure the compliance of the newly generated surface with the size parameters presented by the various size databases.

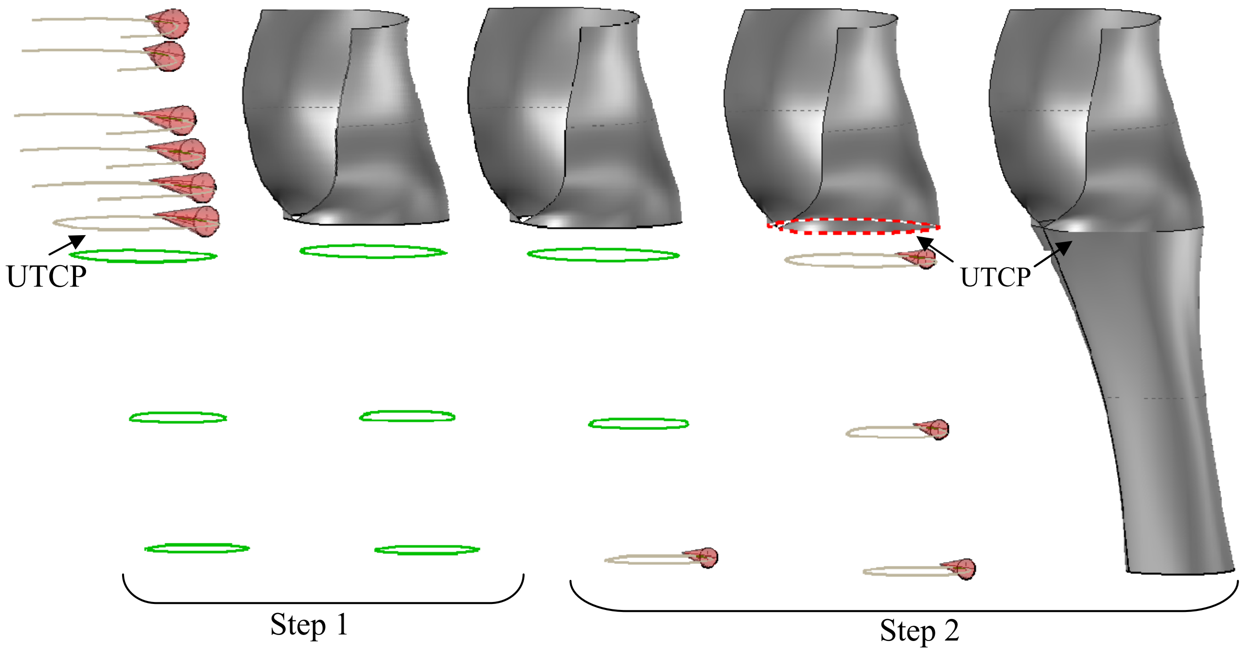
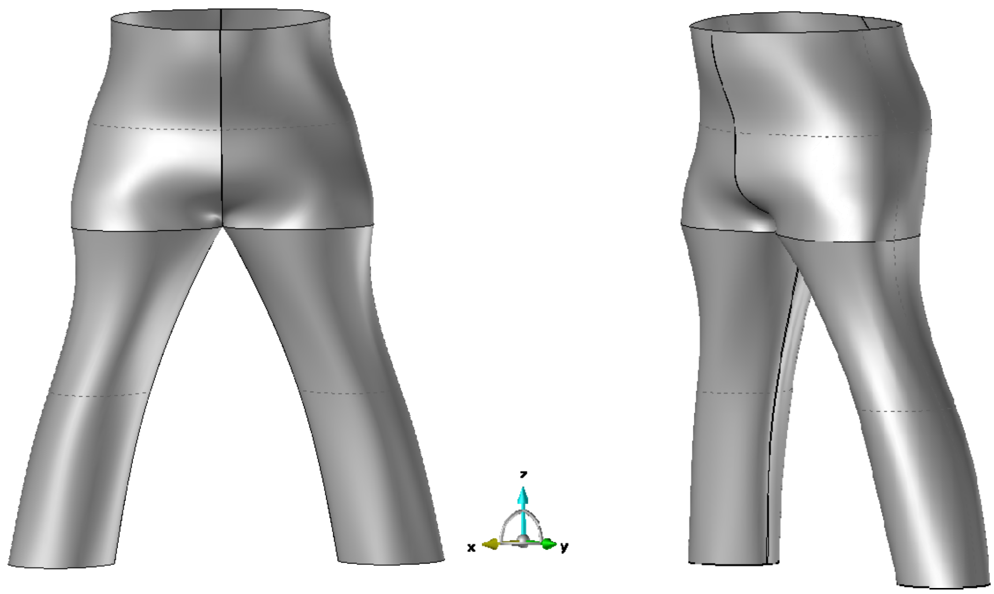


Figure 5-10 Steps of Surface Generation out of Scaled Curves

When an attempt was made to generate a new surface out of the scaled curves, two difficulties arose. There were geometrical disparities between the upper five curves and the lower four curves. This was a consequence of the upper curves being open B-Spline curves, whilst the lower curves were closed B-Spline curves. The software proved incapable of coupling closed curves, which offer a continuous surface, with open curves, which do not. A further problem was that if one surface was created based on the closed curves and a separate surface was made out of the closed curves, the system was incapable of merging them satisfactorily. The root of this problem was the same as that encountered initially; open and closed curves may not be associated within the software. To resolve these problems, the lower curves, namely the upper thigh girth at the crotch point (UTCP), the thigh, knee and the hem at the end of the leg, were split along the inseam position by inserting a 2 mm gap. This effectively converted the lower set of curves into open curves, the same as those forming the upper part of the construction and this device ensured the generation of a smooth, seamless surface all formed using open curves.

To achieve the shape required for virtual modelling, a surface was first generated using the upper five curves and the UTCP. This was followed by generating a second surface using the four lower curves and including the UTCP. In both cases, the UTCP formed a common end contour and thus the surfaces could be combined seamlessly, as illustrated in Figure 5-10, and thus successfully formed the left part of the required trouser template. The completed left section was then mirrored about a vertical axis to form the right half and thus make the complete trouser template, as shown in Figure 5-11.



Front view *Angular side view*

Figure 5-11 Resizable Trouser Template

5.7 Developing Size Databases for 3D Grading

In order to resize and reshape the scaled curves to generate a suite of templates, a table of size parameters was developed using the Excel spreadsheet program. The CAD system in which the template was built facilitated linking with Microsoft applications, so this offered a straightforward approach for making available a wide-ranging set of external values with the parameters of geometrical objects modelled within it. The size dataset is shown in Table 5-3 and includes values for the waist, the low waist, the seat, the body rise, the length of the inseam and the leg hem girth. These figures were taken from the size chart for trousers for men included in the second edition of “Metric

Pattern Cutting for Menswear" written by Aldrich (1990). Looseness control girths 1 and 2, as used in this work, are not incorporated into conventional pattern drafting systems for trousers; consequently their values are not included in established size charts. However, the 3D modelling technique that is being developed is based on sectional curves and measurements are required for these two curves, as they play an important role in defining the trouser silhouette between the seat and the crotch line. They establish the fullness of the trousers between the hip and the thigh. It was therefore assumed that their values would not be less than the value of the seat girth. Considering this, the same value as the seat has been adopted for these two girths, as may be seen in Table 5-3.

The values for the UTCP, thigh and knee were taken from anatomical measurements of the male subject whose scanned data have been used in this research work. The male subject had a waist measurement close to 90cm, which is an established commercial waistband measurement. Hence, the measurements for the UTCP, thigh and knee were incorporated into this specific size and they have been methodically graded for the other sizes.

Table 5-3 Size Table for Men's Trousers

Measurement positions	**Measurements for Men's Trousers without Ease (in cm)** *(Waist as size designation)*								
Waist	**74**	**78**	**82**	**86**	**90**	**98**	**102**	**106**	**110**
Low waist	77	81	85	89	93	100	104	108	112
Seat	92	96	100	104	108	114	118	122	126
Looseness control girth 1	92	96	100	104	108	114	118	122	126
Looseness control girth 2	92	96	100	104	108	114	118	122	126
Body rise	26.8	27.2	27.6	28	28.4	28.8	29.2	29.6	30
Inseam length	78	79	80	81	82	82	82	82	82
Upper thigh at crotch point	54	56	58	60	62	64	66	68	70
Thigh	47	49	51	53	55	57	59	61	63
Knee	36	37	38	39	40	41	42	43	44
Leg girth at hem	41	42	43	44	45	46	46	46	46

The size table has been divided into subsidiary databases for individual sizes between 74cm and 110cm, which are correlated separately from the functional and design ease allowances, as shown in Table 5-4 for size 90, to which they have been added. It is important to note that there is currently neither an established rule nor a formula available to calculate functional ease and design ease for particular types of garment (Petrova and Ashdown, 2008; Gill and Chadwick, 2009). The ease values introduced into this research are included only for purposes of testing the proposed 3D template and can be very simply altered to allow for the preferences of designers and wearers.

A table for a wide range of sizes, including ease allowances may be found in Appendix 5.

Table 5-4 Size Parameters with Ease Allowances for Size 90

Size Parameters	**Measurements in cm**	**Functional Ease**	**Design Ease**	**Final Trouser Measurement**	**Linking Value for Scaled Curves**
Waist	90	5	0	95	47.5*
Low waist	93	5	0	98	49*
Seat	108	5	1	114	57*
Looseness control girth 1	108	5	3	116	58*
Looseness control girth 2	108	5	5	118	59*
Body rise	28.4	1	0	29.4	29.4
Inseam length	82	0	0	82	82
Upper thigh at crotch point	62	7	3	72	72
Thigh	55	6	2	63	63
Knee	40	5	2	47	47
Leg girth at hem	45	-	0	45	45

*Note: * half of the final trouser measurement has been used.*

5.8 Testing

Similarly to the Shirt template described in the previous chapter, the functionality of the resizable trousers template described in section 5.6 was tested, based on the following criteria to ensure that it would function as a drawing platform for 3D clothing development: resizability and automatic grading of 3D clothing; pattern flattening; and fashion drawing in 3D. The test processes have been described in the following sub-sections and the findings are described in the next chapter.

5.8.1 Drawing Platform and Virtual Clothing

Outlines of trousers and shorts were drawn on the 3D trousers template and virtual trousers and shorts were developed from them, as can be seen in Figures 5-12 and 5-13. It may be observed that the definitions of the waistband and the outer side seam are the only ones required to produce a design for trousers and shorts on this 3D trousers template; it was built from two symmetrical halves and the inseam lines were already predefined.

The link length-based region creation mode was followed to create virtual clothing from the drawn outlines and the effect of using different link lengths and vertex angles was examined.

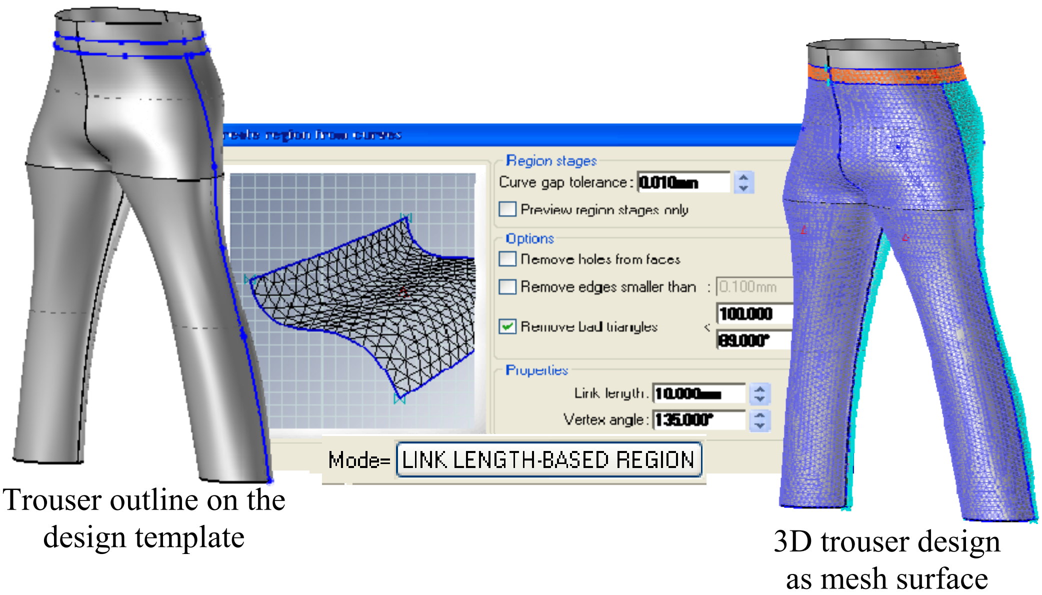
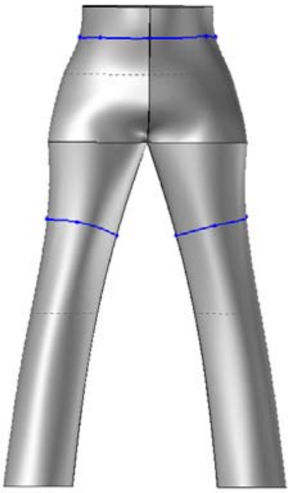
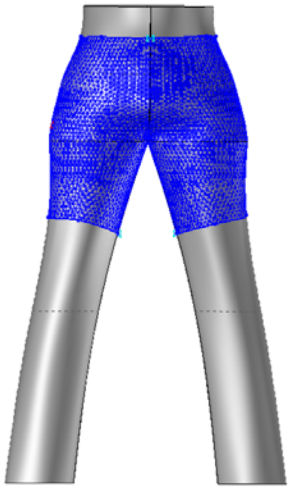


Figure 5-12 Designing Trousers on the Resizable Template



Shorts outline on the design template



3D Shorts design as mesh surface

Figure 5-13 Designing Shorts on the Resizable Template

5.8.2 Resizability and Grading in 3D

To check the resizability of the trouser template, values for each of the curves were manually altered. Figures 5-14 and 5-15, for example, illustrate the effects of changing the inseam length and the body rise manually from the parameter list. The effect of these changes on the virtual clothing designed using the template was also evaluated.

Different size databases, which were previously developed using the Excel spreadsheet programme, were linked with the template to execute automatic grading in 3D. The effect of the size changes on the virtual clothing created using the template was also evaluated.

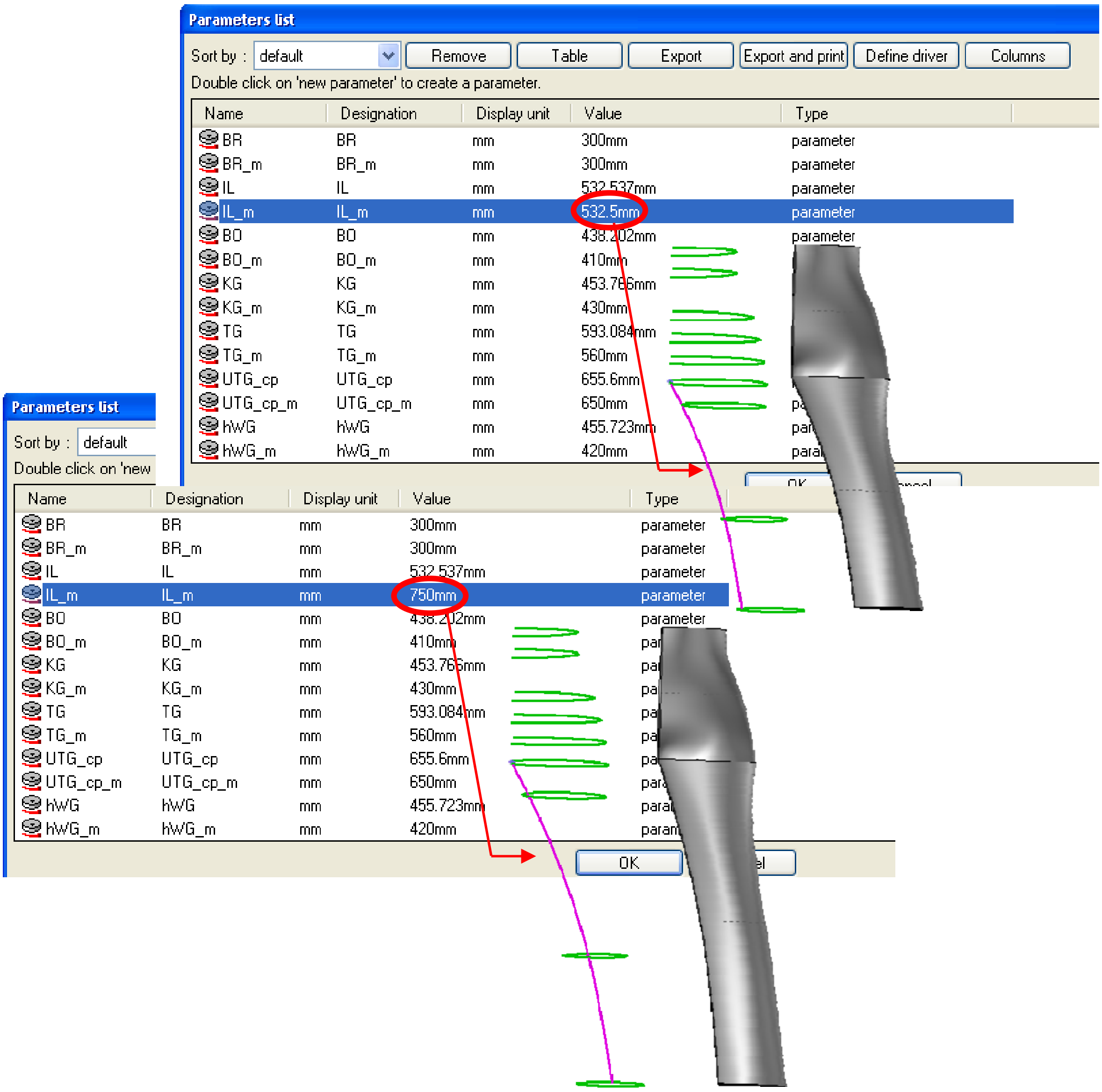


Figure 5-14 Effect of Changing the Inseam Length Manually

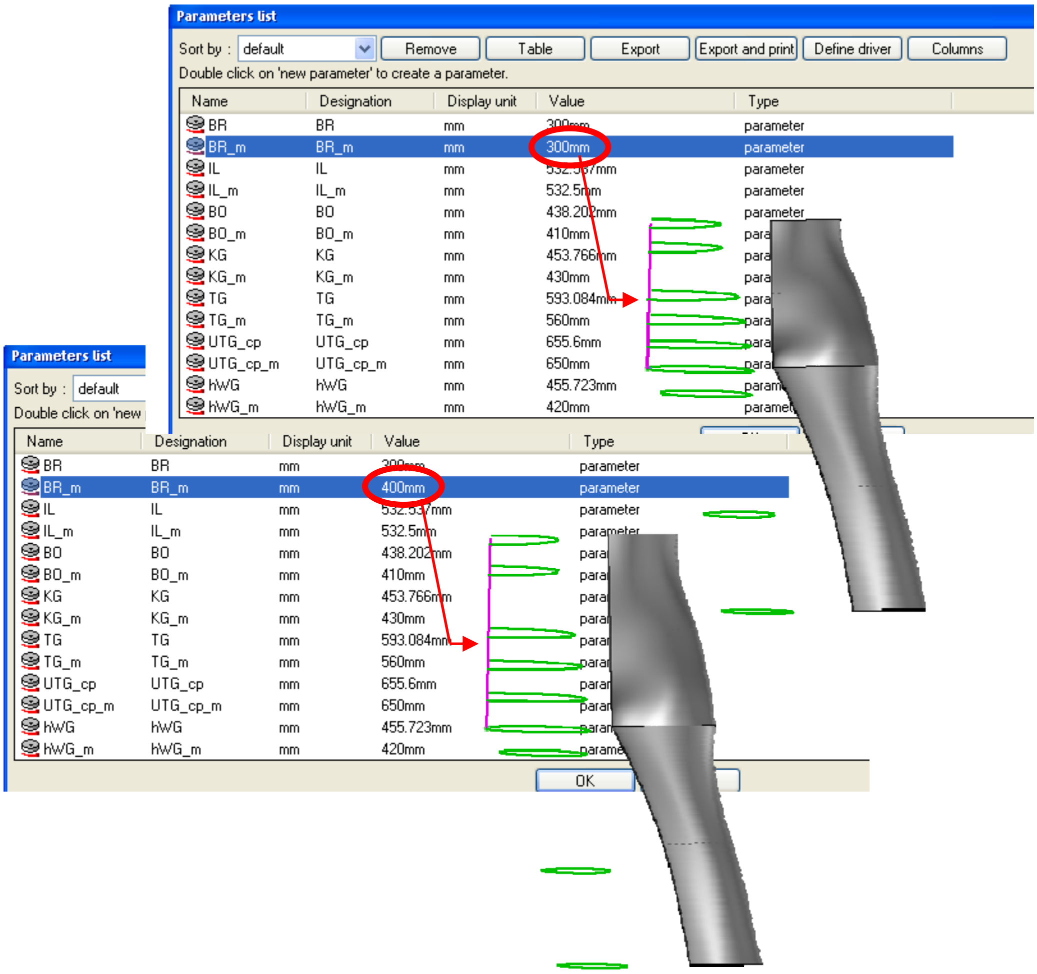


Figure 5-15 Effect of Manual Change of the Body Rise

5.8.3 Flat Pattern Extraction

Finally, the 3D designs were automatically flattened into 2D pattern pieces using the flattening tools. The option to "match edge lengths" was kept activated to ensure the dimensional integrity of the flat pattern pieces with the 3D design.

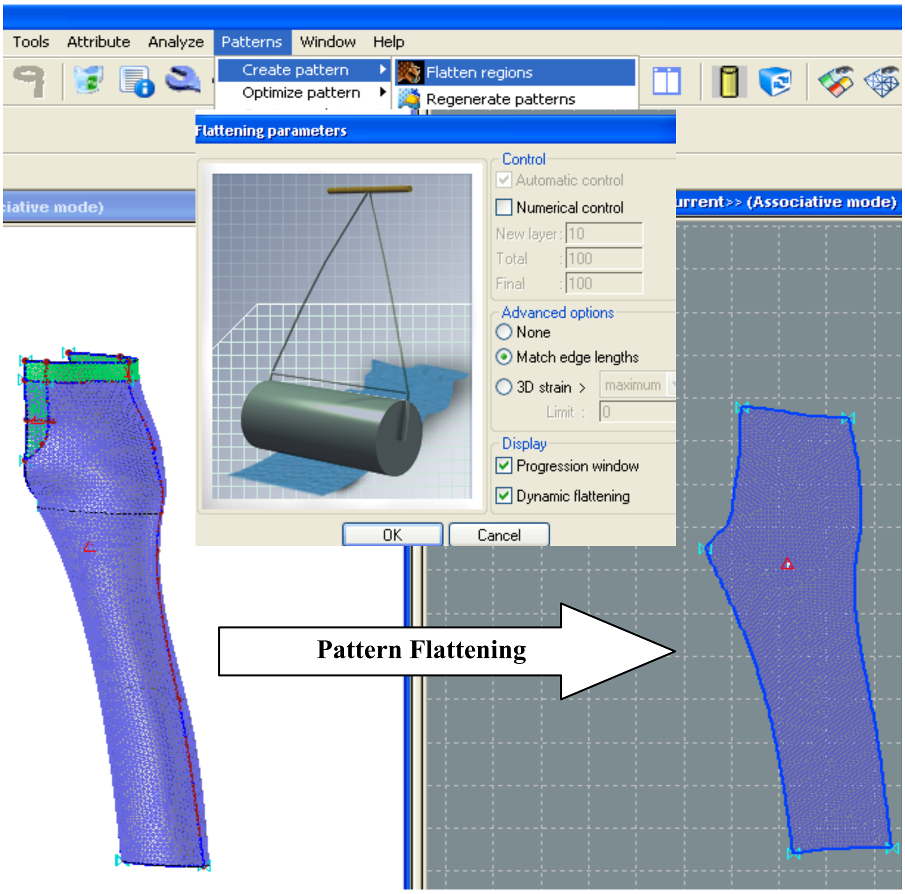


Figure 5-16 Flat Pattern Extraction from Virtual Trousers

Figure 5-16 shows an example of flat pattern extraction of the front part of a virtual pair of trousers. Similarly, flat pattern pieces from differently graded virtual trousers were extracted and measurements of all of the boundary edges of the flattened pattern pieces were checked.

5.8.4 Fashion Drawing and Rendering in 3D

The various rendering options available within the DCTT software suit were applied to generate different visualisations in the 3D format. Figure 5-17 shows the effect of solid surface rendering after changing the rendering mode between the available options, and Figure 5-18 represents an example of producing a stripe effect using image data. Similarly, different graphical surfaces were applied to the virtual shirt prototypes to exploit the availability of fashion drawing and rendering in a 3D format.

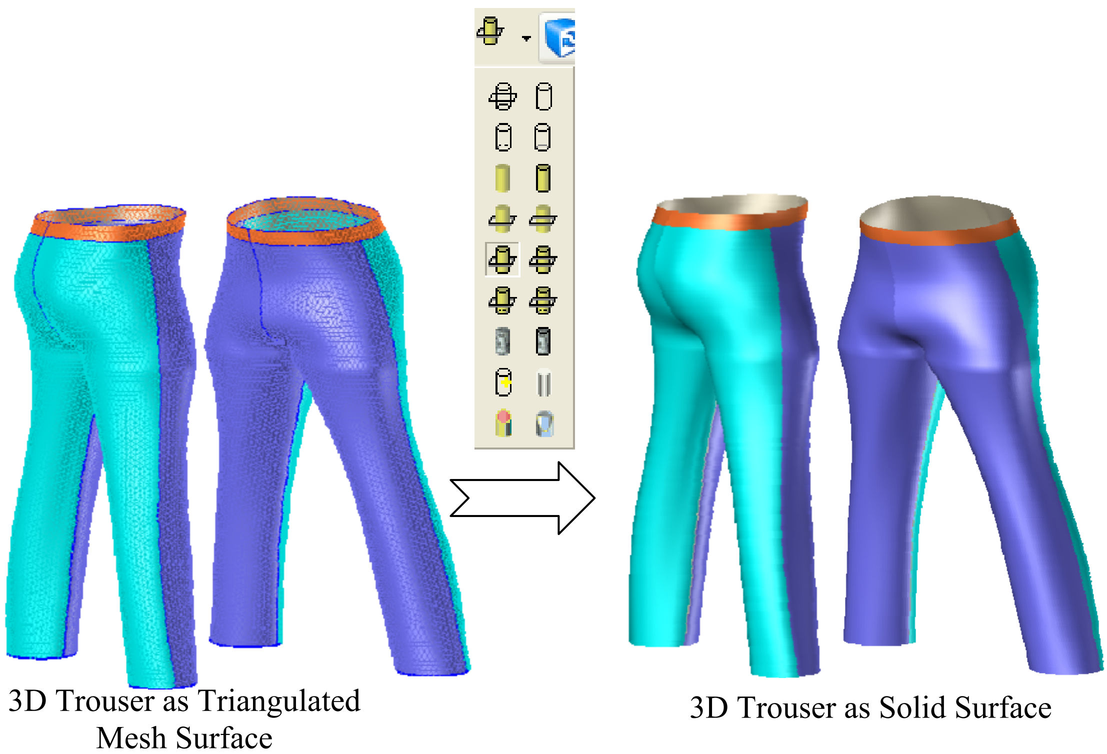


Figure 5-17 Use of Rendering Tools for Different Visualisation

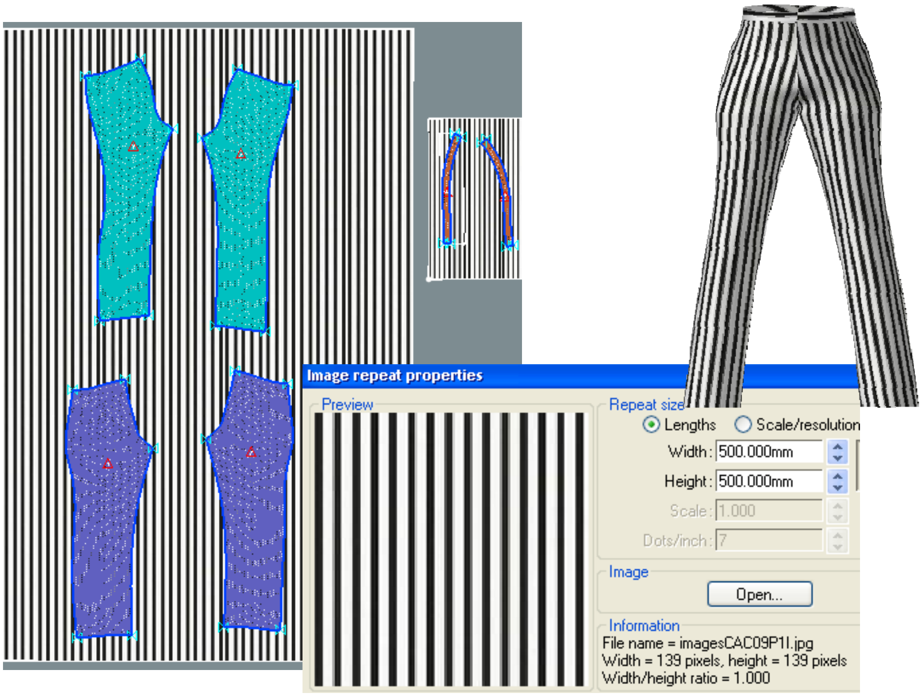


Figure 5-18 Applying a Stripe Effect to the Trouser Surface

5.8.5 Physical Prototype

A 3/4 length pair of men's trousers was designed on the trouser template after grading it into size 86 as presented in Appendix 5 and a prototype was made to justify the usability of flattened pattern pieces in garment manufacture. Figure 5-19 illustrates the 3D design and the flattened patterned pieces including a seam allowance. 100% linen woven fabric (plain weave, 175 g/m^2) was used to make the physical prototype. Manufacturing specifications of the 3/4 length trouser prototype are presented in Table 5-5. Nonwoven fusible interfacing was used in the waistband and hook and eye fasteners were used in the front waistband and fly closing. The manufactured prototype is presented in Figure 5-19. Trials of the physical prototype were arranged with live models to check the general fit quality.

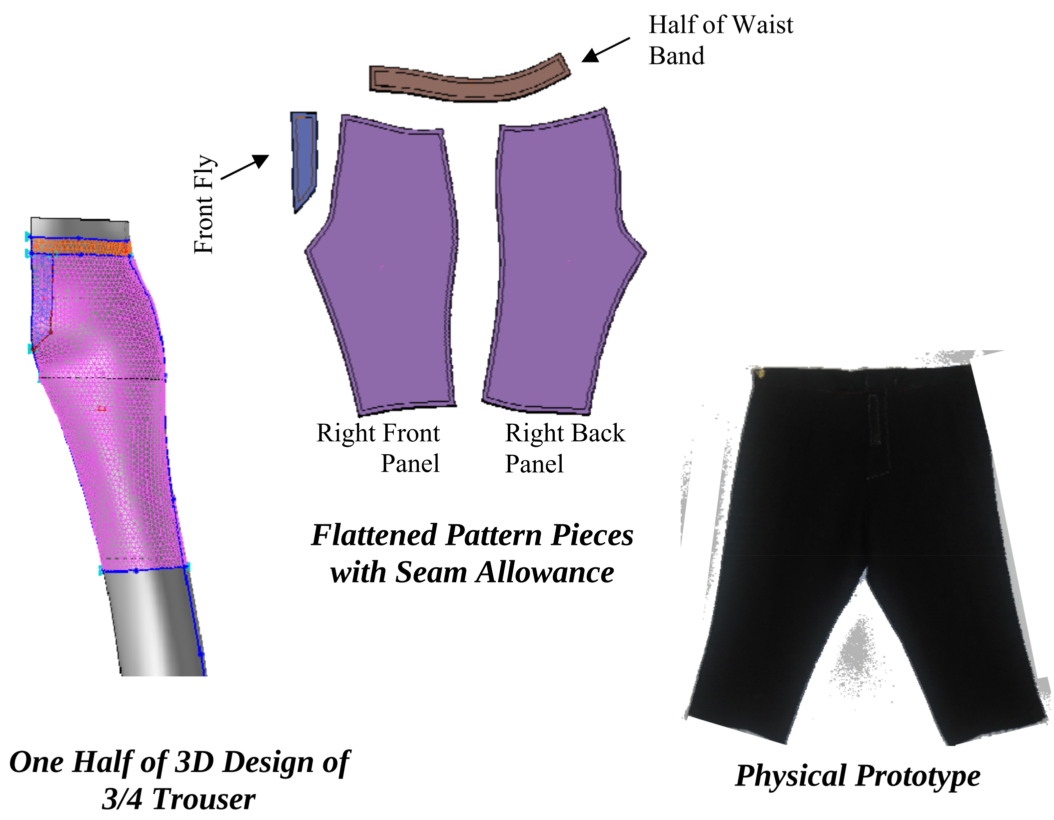
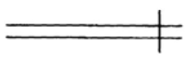
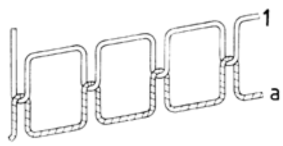
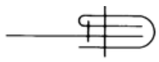
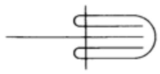


Figure 5-19 3D Design, Flattened Pattern Pieces and Physical Prototype

Table 5-5 Specifications of 3/4 Length Trouser made in Size 86

	Seam/Joining Area	**Seam Class**	**Seam Illustration**	**Stitch Type and Class**	**Stitch Illustration**
1	Inseams	1.01.01		Lock Stitch (301)	 1= Needle thread, a = Bobbin thread
2	Side seams				
3	Front rise				
4	Back rise				
5	Waistband joint	3.03.06			
6	Fly joint with left front panel	3.05.03			

Chapter 6: Results and Discussion

6.1 Functionality

6.1.1 3D Drawing Interface and Virtual Clothing

Both of the shirt and trouser templates developed within the framework of this research have been found to be fully functional as appropriately sized 3D drawing boards which allow sketching and development of virtual clothing on their surfaces. Using 3D drawing tools, it was found possible to draw any open or closed curve on them, as can be seen in the Figures 6-1 and 6-2. With the help of mesh generation tools, it was found possible to create a layer of triangulated mesh network out of the curves drawn as design outlines on the templates. Such a mesh network automatically adopts the surface geometry of the template and it can also be visualised as an adjacent layer of a rigid surface. This provides an opportunity of creating versatile clothing designs on the templates.

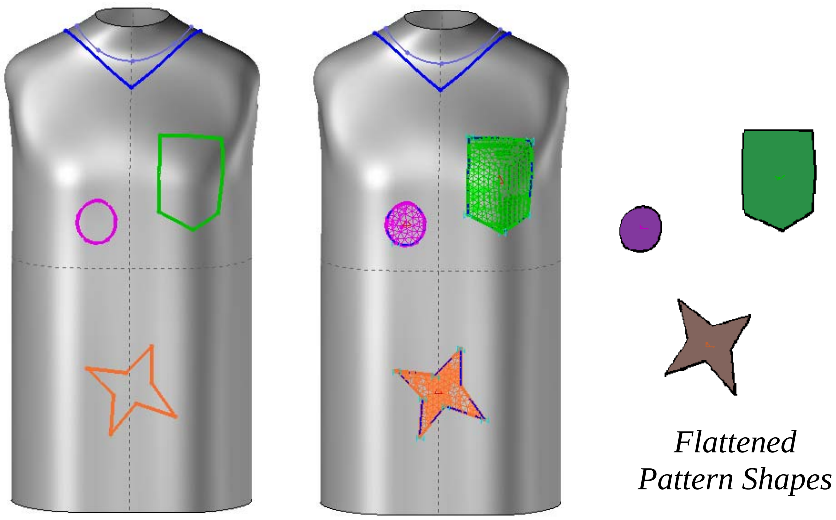


Figure 6-1 Example of Curves and Shapes drawn on the Shirt Template

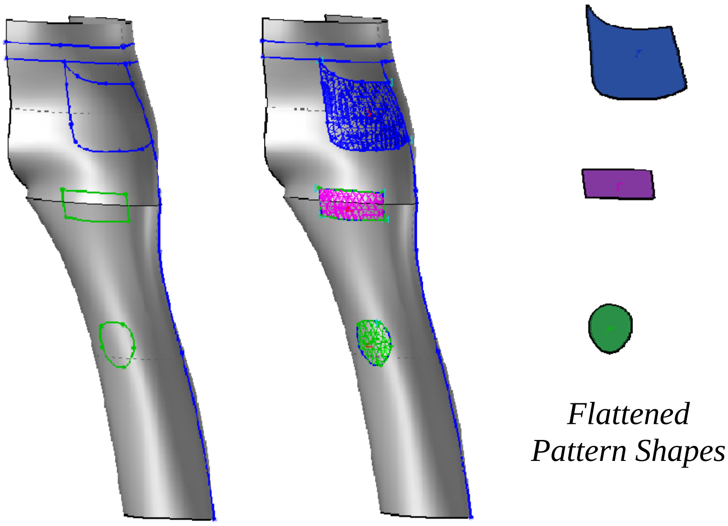


Figure 6-2 Example of Curves and Shapes drawn on the Trouser Template

Outlines of long sleeves and short sleeves were successfully drawn on the shirt template. It has been found that the group of men's shirts that have sleeves joined at the armhole areas can easily be designed on the 3D shirt template. Even the design of a suit jacket, as can be seen in Figure 6-3, can also be developed on it.

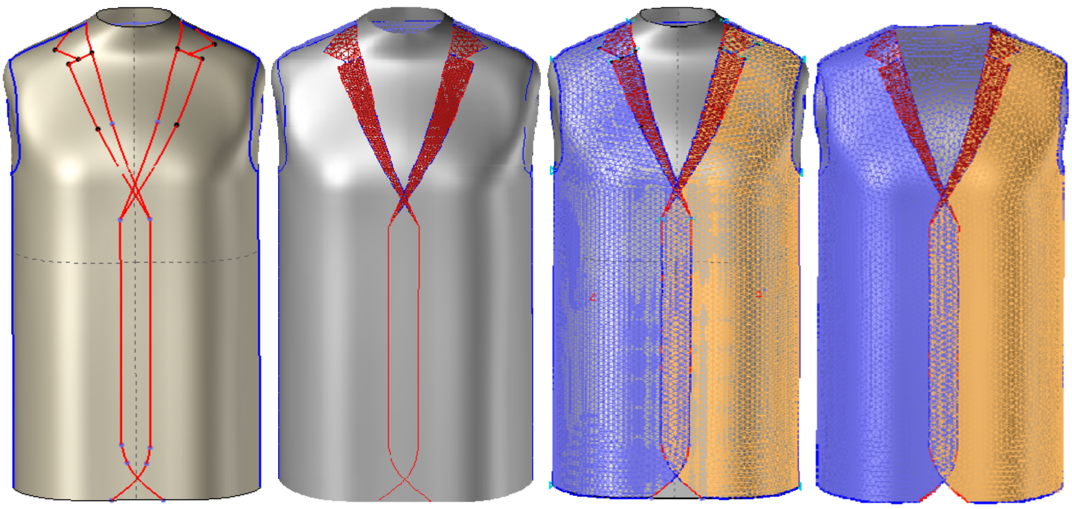


Figure 6-3 Designing Virtual Suit Jacket on the Shirt Template

Similarly the trouser template was found to be suitable for developing both virtual trousers and shorts on it. As the inseam lines are already defined in the trouser template with the help of a 2mm wide gap in each leg, only two outlines, namely the out seams and a waist line are enough to develop the design of a pair of virtual trousers. For shorts, additionally an outline for the bottom hem of each leg is required. Figure 6-4 demonstrates a design for a pair of shorts with conical bottom hem at the front and at the back.

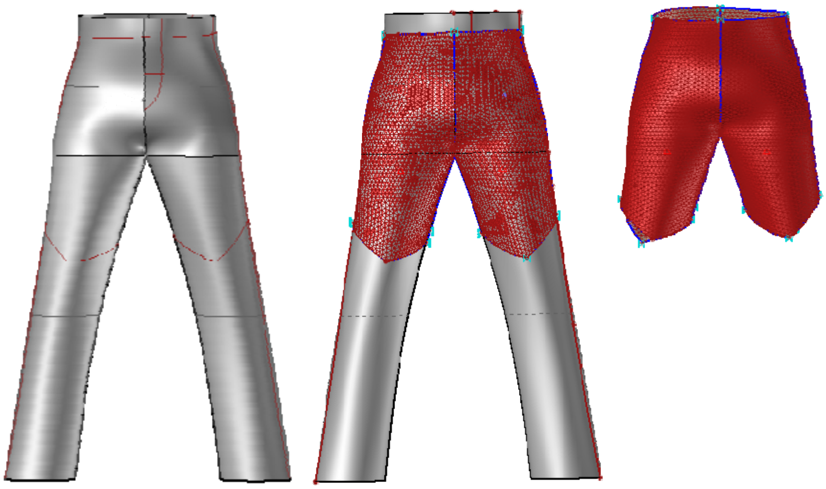


Figure 6-4 Designing Virtual Shorts on the Trouser Template

However, as the sleeves were created as separate parts of the 3D shirt template, a design limitation was found prevailing in it. For example, the raglan sleeve design could still be visualised on the shirt template but could not be flattened as a single pattern piece as can be seen in Figure 6-5. A modified shirt template with sleeves merged with body parts may be developed to address this problem. If the sleeves can be seamlessly merged with the body of the shirt template, it will not be a problem to develop a raglan sleeve on it and subsequently flatten it into 2D.

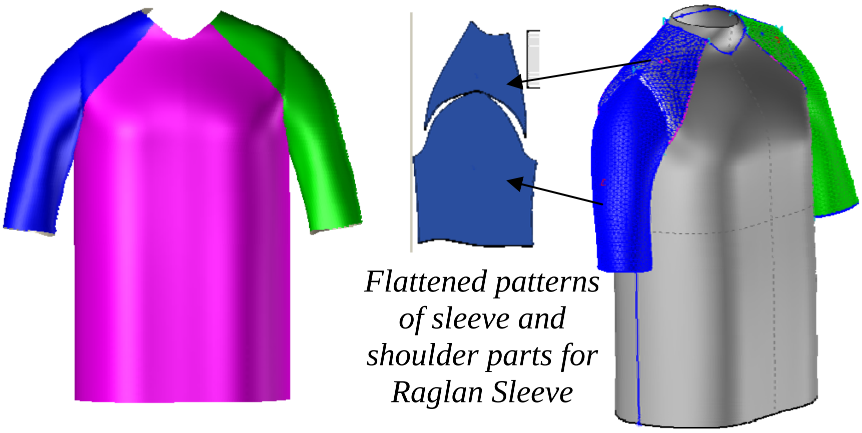


Figure 6-5 Visualisation of Raglan Sleeve and Flattened Patterns

It is also found that designs of all types of collar could not be developed on the shirt template. A standard straight collar (Figure 6-6 A) and two-piece collars such as a standard straight collar with a stand (Figure 6-6 C) and a shirt collar with a stand (Figure 6-6 D) can easily be developed on the shirt template. Figure 6-7 illustrates a two-piece shirt collar with a stand. However, it is not possible to develop a one-piece shirt collar (Figure 6-6 B) on the shirt template, as any overlapping surface cannot be flattened into a single 2D component using the existing flattening tools. However, for the two-piece shirt demonstrated in Figure 6-7, the collar and stand designs overlap each other on the shirt template, but they can be flattened separately into a 2D form.

Considering the limitation in collar design, it can be recommended that a library of different 3D collars would need to be included be necessary within a 3D CAD system, wherefrom designers could easily pick the right one and change the size to match the neck size of the shirt.

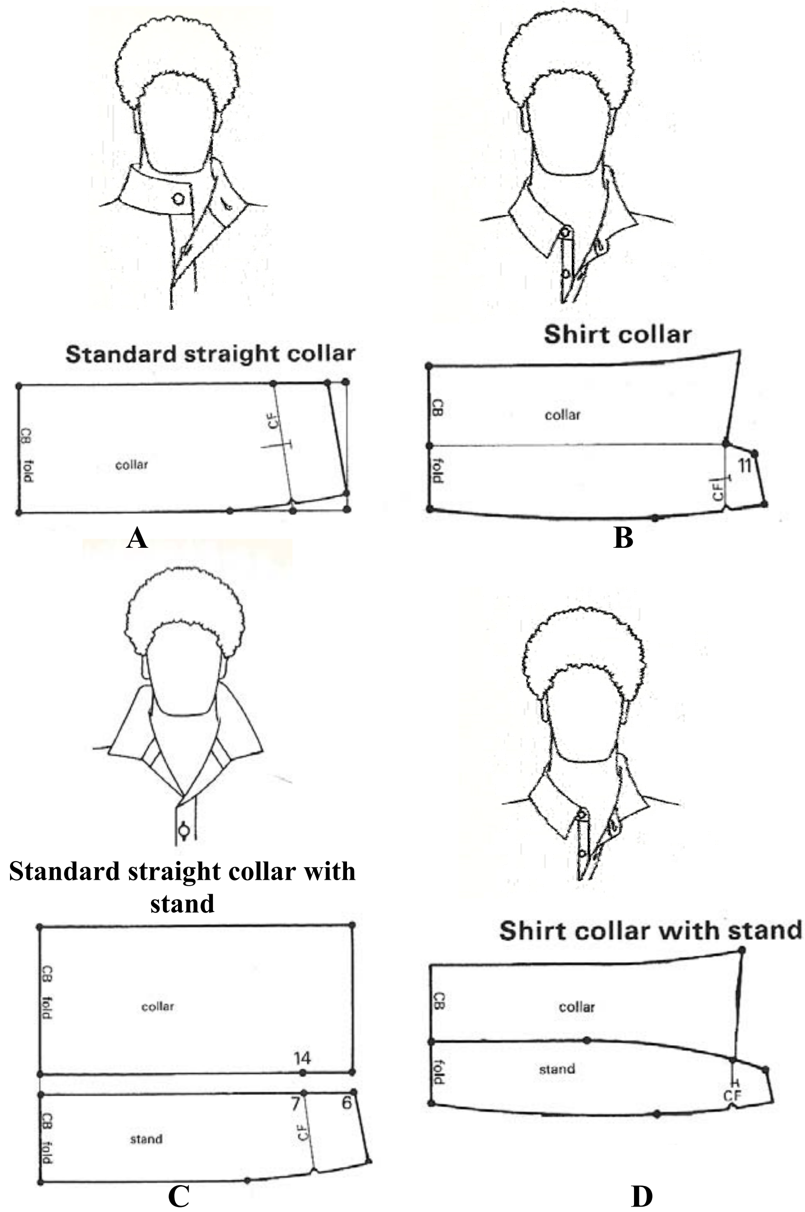


Figure 6-6 Different Types of Shirt Collars (Aldrich, 1990)

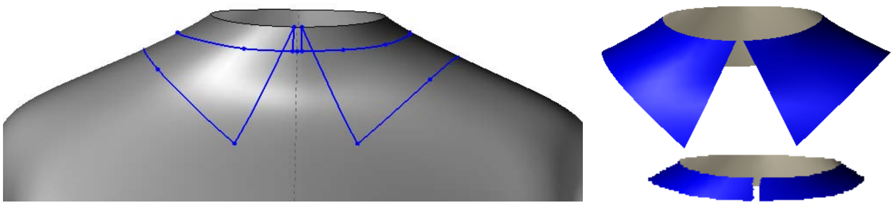


Figure 6-7 Development of Two-Pieces Collar on Shirt Template

6.1.2 Mesh Generation Properties

Link length and vertex angle are two variable factors in the link-length-based mesh generation process. It was found that link length directly influenced the quality of the generated mesh surface and the flattened pattern pieces, and the speed of mesh generation and pattern flattening were also directly affected. Tables 6-1 and 6-2 present the effect of the choice of link length on the mesh generated on the shirt and on the trouser template respectively. In both cases, the smaller the link length of the triangles in the mesh structures, the higher the mesh surface area, and the lower the mesh generation and pattern flattening speeds. In the computer system [Intel (R) Core ™ 2 Duo processors (E7400 @2.80 GHz, 2.79 GHz); 4 GB of RAM and Microsoft XP Professional Version 2002 (32-bit Operating System)] used in this work, the mesh generation time is below 1 second when the link length is above 15mm. But the quality of generated mesh surface is relatively poor. This is prominent in Figures 6-8 and 6-9 that illustrate the generated mesh surface and flattened pattern when the link length was taken as 100 mm. For the shirt front part, the generated mesh surface did not follow the contours of the drawn outlines correctly. Especially at the neck curve and the armhole curve areas, the generated surface hardly followed the geometry of the drawn outline at all. In the case of a front panel of a pair of trousers, which can be seen at the Figure 6-8, the surface geometry was not correctly reproduced when the link length was taken as 100 mm.

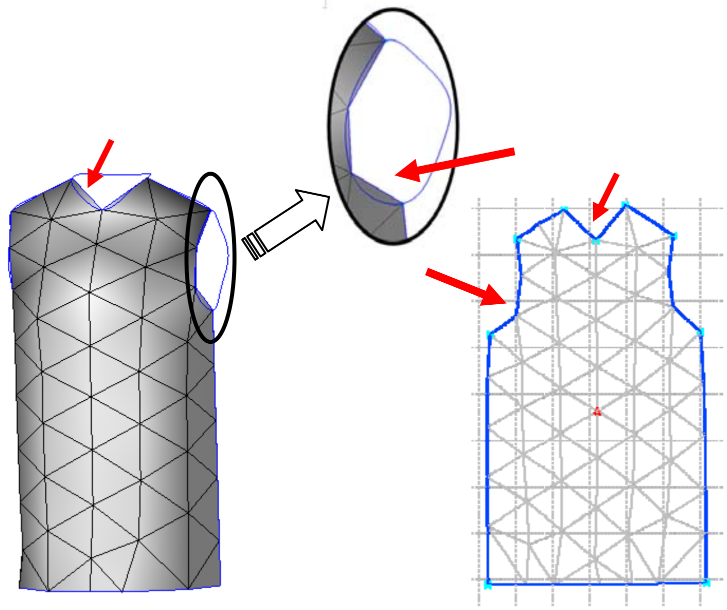


Figure 6-8 Mesh Surface and Flattened Pattern at 100 mm Link length

Table 6-1: Effect of Link Length on Pattern Generation of Shirt's Front Panel

Link Length (mm)	Mesh Generation	Number of Triangles	Meshing Time	Mesh Surface (mm^2)	Flattening time
100	Yes	85	<1 second	431266.204	<1 second
50	Yes	393	<1 second	435492.934	<1 second
25	Yes	1594	<1 second	436543.46	<1 second
15	Yes	4356	<1 second	436701.373	13 second
10	Yes	9839	1 second	436753.486	1 minute, 24 seconds
5	Yes	39735	5 seconds	436788.155	30 minutes, 52 seconds,
4	Yes	62048	8 seconds	436792.417	1 hour, 12 minutes, 38 seconds
3	Yes	110485	15 seconds	436795.816	Program Collapse
2	No	-	-	-	-
1	No	-	-	-	-

Table 6-2: Effect of Link Length on Pattern Generation of Trouser Front Panel

Link Length (mm)	Mesh Generation	Number of Triangles	Meshing Time	Mesh Surface (mm^2)	Flattening time
100	Yes	46	<1 second	226903.595	<1 second
50	Yes	221	<1 second	235445.804	<1 second
25	Yes	869	<1 second	237279.252	1 second
15	Yes	2394	<1 second	237716.080	2 seconds
10	Yes	5464	1 second	237888.423	18 seconds
5	Yes	21916	2 seconds	237986.605	6 minutes, 47 seconds
4	Yes	34369	4 seconds	237998.725	16 minutes, 50 seconds
3	Yes	61115	7 seconds	238008.382	46 minutes, 14 seconds
2	Yes	137730	20 seconds	238015.209	Program Collapse
1	No	-	-	-	-

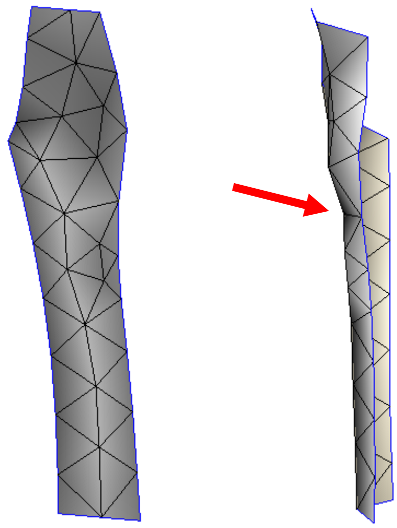


Figure 6-9 Mesh Structure and Flattened Pattern at 100 mm Link length

When the link length was defined as 5mm or less, both mesh generation and pattern flattening processes were found to be very slow. Particularly the total flattening times required in these cases were very high and could not be considered feasible for clothing designers. The flattening engine did not work at all when the link length was set below 4 mm for shirts and 3 mm for trouser designs respectively. With link length below 3 mm for shirts and below 2 mm for trouser designs, the mesh generation engine was found to be unable to handle the large number of calculations.

The optimum link length, considering the quality of the mesh surface and the flattened pattern pieces and the speeds of mesh generation and pattern flattening, was found to be between 10 mm and 15 mm for both shirt and trouser design.

It has been found that the vertex angle does not influence the quality of the mesh surface, rather it only influences the number of individual curves formed along the boundary line of the mesh surface and of the flattened pattern pieces. When a vertex angle between 120º and 160º was selected, the boundary line was found to be segmented at every corner point available. This helped to measure each of the relevant edges of the pattern individually, such as the neckline, shoulder, armhole curve and side seams.

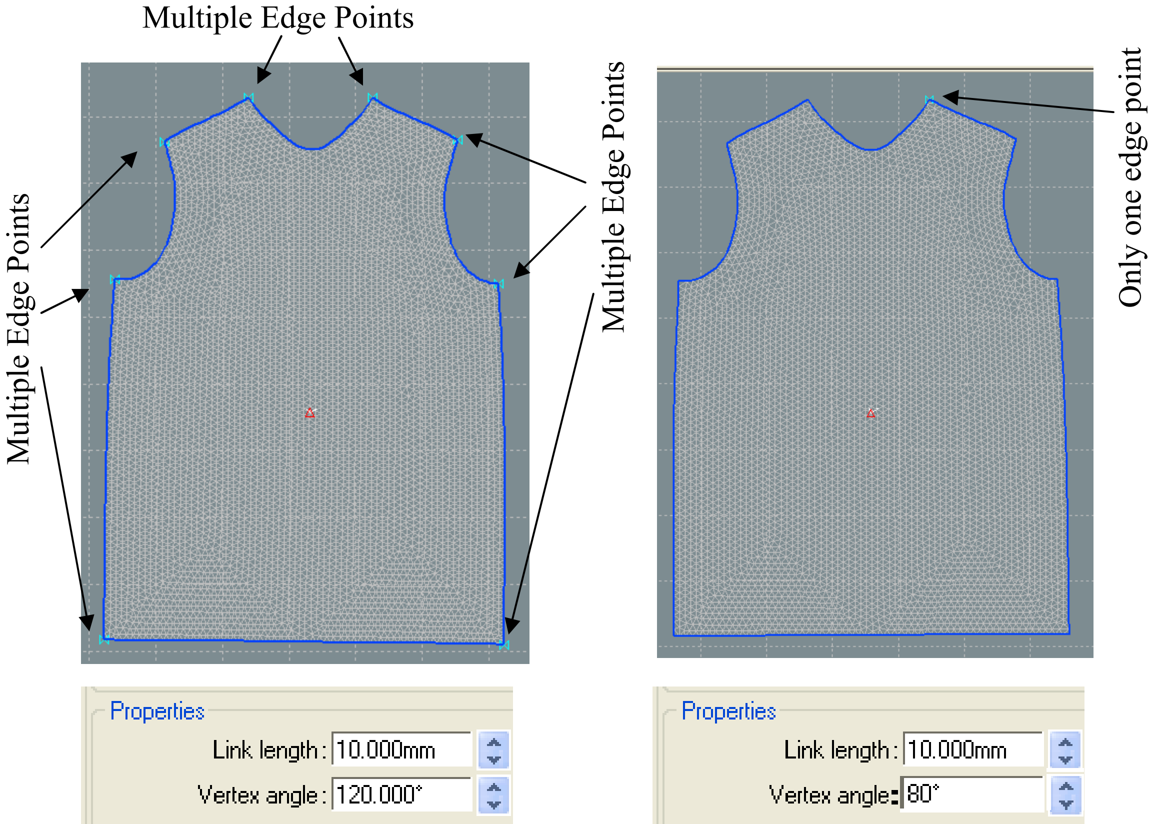


Figure 6-10   Effect of Vertex Angle on Pattern

However, when a vertex angle below 120º was selected, the boundary line was found not to be segmented at every corner point, which did not allow measurement of the pattern edges individually. Any vertex angle above 160º and up to 180º produced too many segmented points which were also not helpful from the pattern designing point of view.

6.1.3 Resizability and Variable Silhouette

Virtual clothing developed on one of the 3D design templates is maintained in a location adjacent to the top layer of the surface of the 3D templates. The geometry of the virtual clothing generated on the 3D template is dependent on the geometry of the template. As a result, any change in size and shape of the 3D template is automatically reproduced in the virtual clothing developed on it. The shirt template is resizable using 12 parameters and the trouser template is resizable using 11 parameters. The parameters of both of the templates can be changed individually or in a group.

It was found that a variable silhouette could easily be produced by changing the values of relevant parameters. For example, when the waist girth measurement of the shirt template was reduced from 11.6 cm to 10.6 cm, keeping all other size parameters unchanged, a silhouette of a tailored shirt can be produced, as can be seen in Figure 6-11.

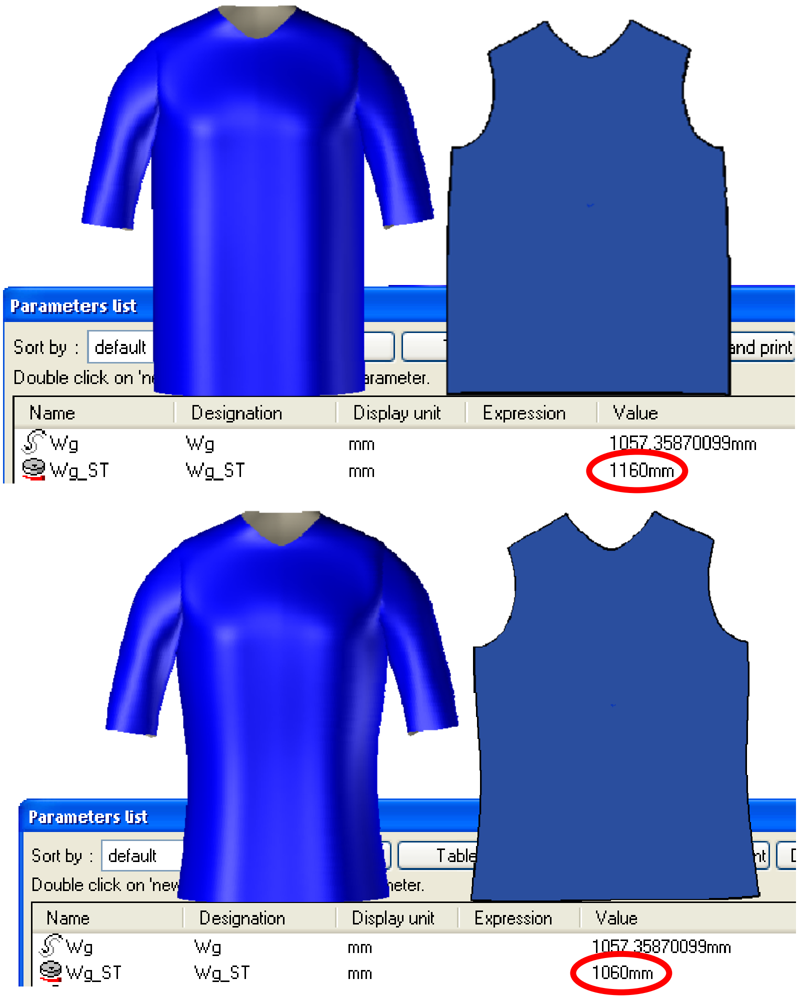
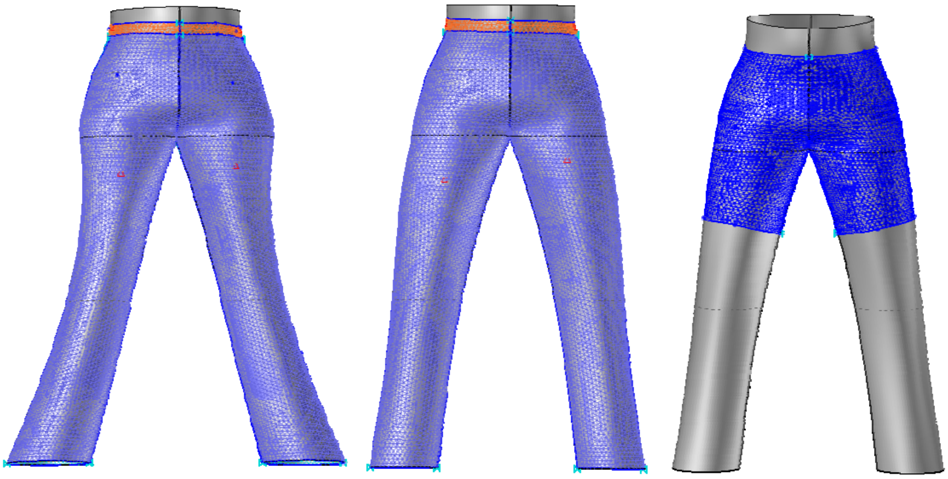


Figure 6-11 Variable Shirt Silhouettes

Similarly, a variable silhouette can be developed using the trouser template also. Figure 6-12 demonstrates examples of variable trouser and shorts silhouettes developed by changing the measurements of the leg openings and thigh girths.

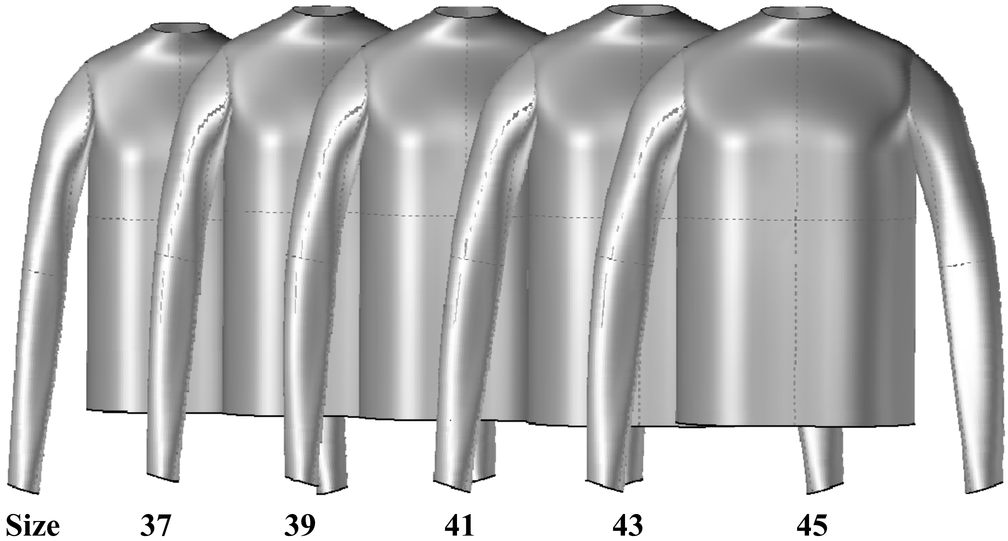


When Leg Opening is enlarged *When Thigh Girth is enlarged*

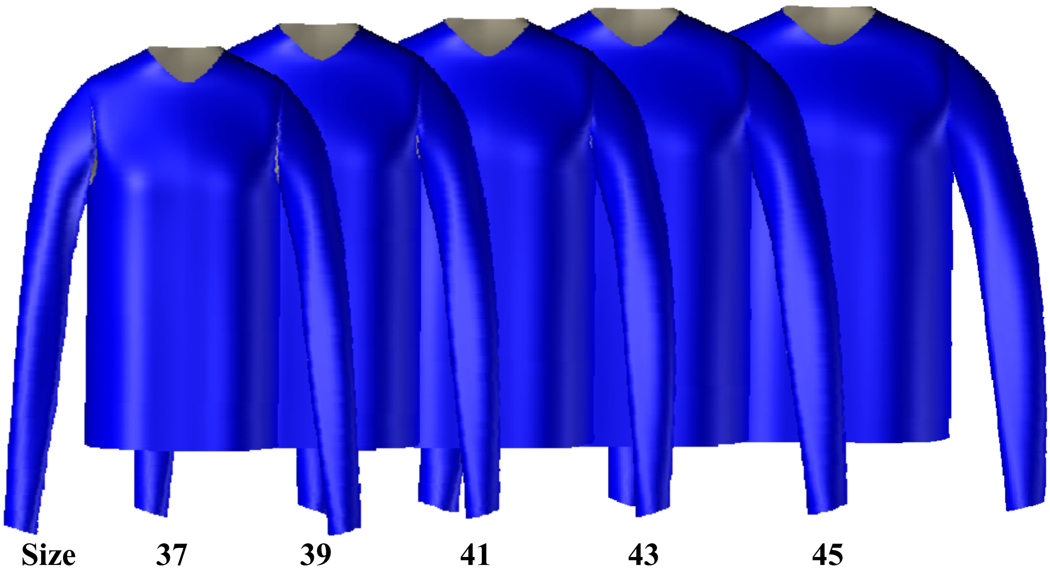
Figure 6-12 Variable Trouser and Shorts Silhouettes

6.1.4 Automatic Grading in 3D

It has been found that the virtual garments created using this technology are resizable by incorporating figures from the appropriate size databases developed previously. Hence, this facility provides an opportunity for successfully executing 3D grading. After drawing the virtual shirt, the garment may also have its size varied by changing the size of the design platform. Figure 6-13 depicts the shirt template and a virtual long sleeved shirt designed on it in different sizes, which were produced by incorporating the size databases for sizes 37, 39, 41, 43 and 45 presented in Appendix 4.



Shirt Template converted into Different Sizes



Virtual Long-sleeve Shirt Grading into Different Sizes

Figure 6-13 Examples of 3D Grading using the Shirt Template

Figure 6-14 illustrates the 3D grading of a virtual short-sleeved shirt following the same procedure as that adopted for the long sleeved version.

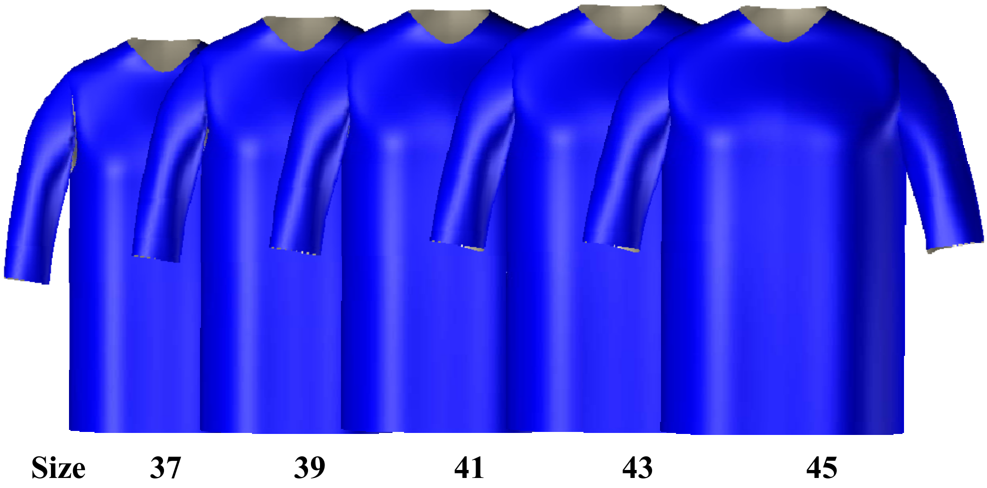


Figure 6-14 Short Sleeve Shirt graded into different Sizes

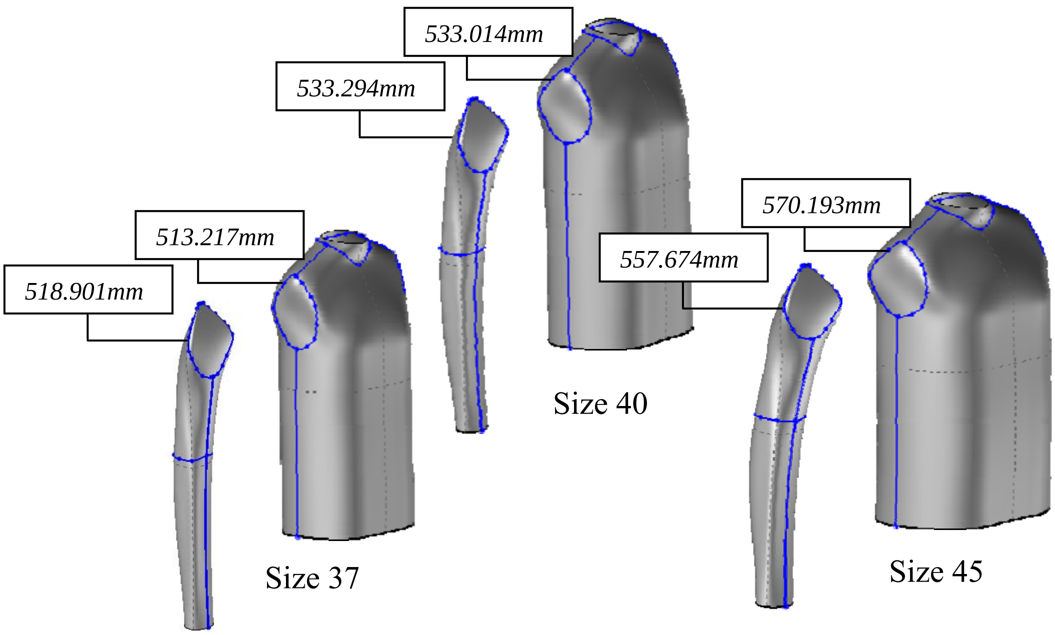


Figure 6-15 Armhole Measurements in Body and Sleeve Parts of Shirt Template in Different Sizes

It was, however, found that the armhole of the shirt design did not change equally in both the sleeve part and in the body part of the shirt template, as can be seen in Figure 6-15, and manual correction was required. Size 40 was selected as a base size to draw outlines of virtual shirt on the shirt template. Armholes are drawn on both the body and sleeve parts, keeping almost equal measurements. When 3D grading was applied using the size databases presented in Appendix 4, the size of the armhole curves on the body part changed significantly from those of the armhole curves on the sleeve parts of the shirt templates and the discrepancies were found to be greater in the larger sizes. For size 45, the armhole curves on the body part were found to be about 1.3 cm bigger than the armhole curves on the sleeve parts. Whereas for size 37, the armhole curves on the body part became about 5 mm smaller than the armhole curves on the sleeve parts.

This problem arose because the armhole was not considered as a scaling parameter and was not incorporated within the scaling procedure for the construction curves of the shirt template. To address this problem, an attempt should be taken in future to merge the sleeve parts with the body part of the shirt template so that both sleeve and body have a common armhole curve and also the length of the armhole should be designated as a parameter in the scaling procedure. However such a problem was not experienced with the trouser template. Figure 6-16 shows the automatic grading in 3D of a simple left-front panel developed on the design template when, for example, the sub-databases of sizes 78, 86 and 106, presented in Appendix 5, are individually linked with the 3D template. This is because all parameters relevant to trouser sizing were included in the scaling process while constructing the trouser template.

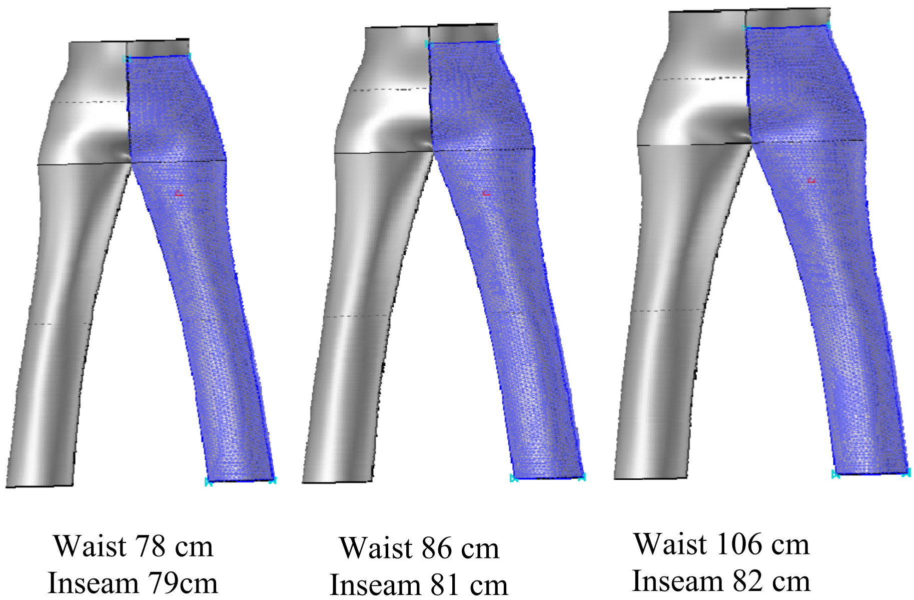


Figure 6-16 Example of Automatic Grading in 3D

6.1.5 Flattened Patterns

The surface of the virtual clothing generated on the 3D templates could be completely developed into 2D by the implementation of a flattening engine. The flattened pieces maintain the exact dimensional properties of the virtual trousers as a consequence of the efficiency of the flattening engine available within the DCTT software suite. It has been found that the edge lengths of any 3D design were almost unchanged after flattening into 2D, as can be seen in Figure 6-17.

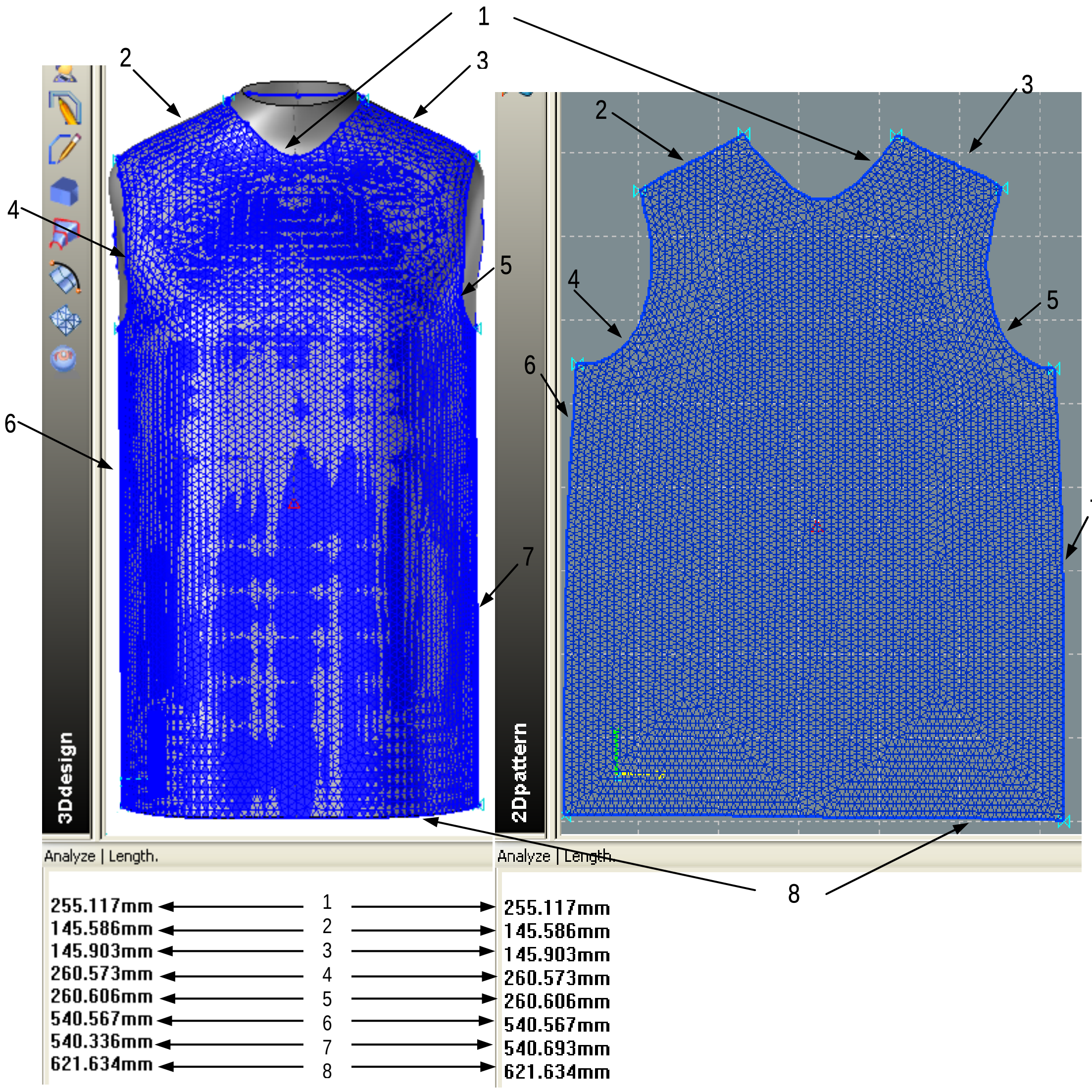


Figure 6-17 Length Analysis of Flattened Shirt Pattern of Size 41

The lengths of seven out of the eight edges of the shirt front panel designed on the shirt template, remained unchanged in the flattened pattern piece, as shown in Figure 6-17. Only the length of one edge (number 7 in the figure) got changed less than half of a millimetre, which is negligible in context of clothing design. So the flattened pattern pieces from this technology can be used directly as production patterns after the addition of suitable stitch and seam allowances.

However a limitation of the existing flattening engine was found in flattening one half of either, a front or back panel of the 3D shirt design. The edge of the pattern that lies along the centre line of the body part of shirt template was not straight anymore after flattening, although it was drawn as a straight line in 3D, as can be seen in Figure 6-18. This demands an improvement in the flattening engine so the complete vertical alignment of the centre line can always be maintained in the flattened pattern pieces. Fang and Ding (2008) demonstrated flattening of a bodice front where the central line and waist line always remained straight and intersected at right angles in the flattened pattern.

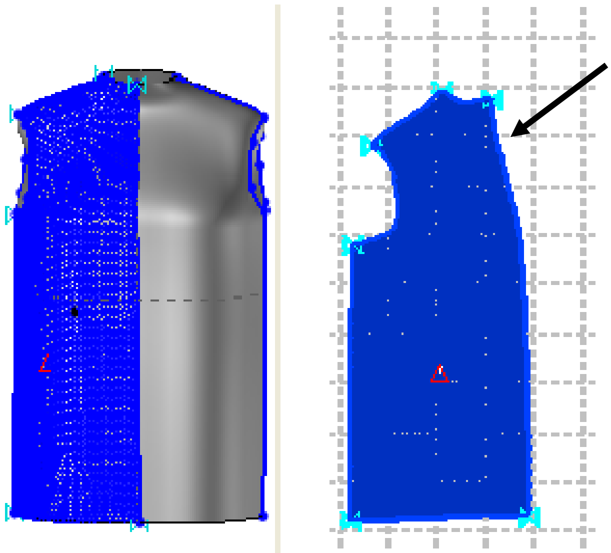


Figure 6-18 2D Design and Flattened Pattern of one half of Shirt Panel

However, within the existing facility, a complete front part of a shirt can be flattened into 2D and then divided into two equal parts by drawing a line in the middle, as demonstrated in Figure 6-19. This requires the availability of pattern division and splitting tools within the 2D pattern modification of a clothing CAD system.

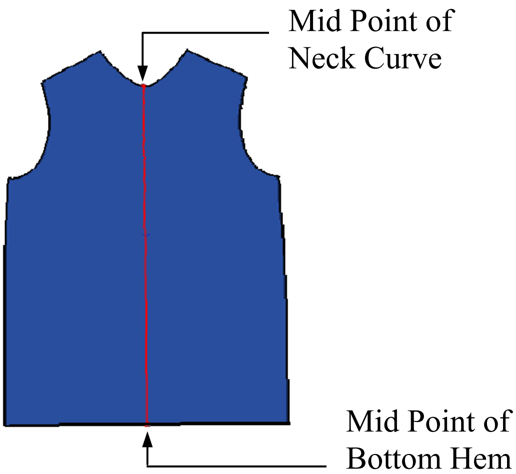


Figure 6-19 Dividing a complete Front Panel into two Parts

In the case of the trouser template, the flattened pattern pieces were found to maintain their dimensional integrity with their 3D design. As, for example, demonstrated in Figure 6-19, four out of five edges of a front leg panel maintained exactly the same measurements when analysed in 2D. Only the outer side seam (number 2 in Figure 6-20) suffered any change and as can be seen in Figure 6-20, this variation was less than a millimetre, which is in clothing manufacture is much smaller than the acceptable tolerance.

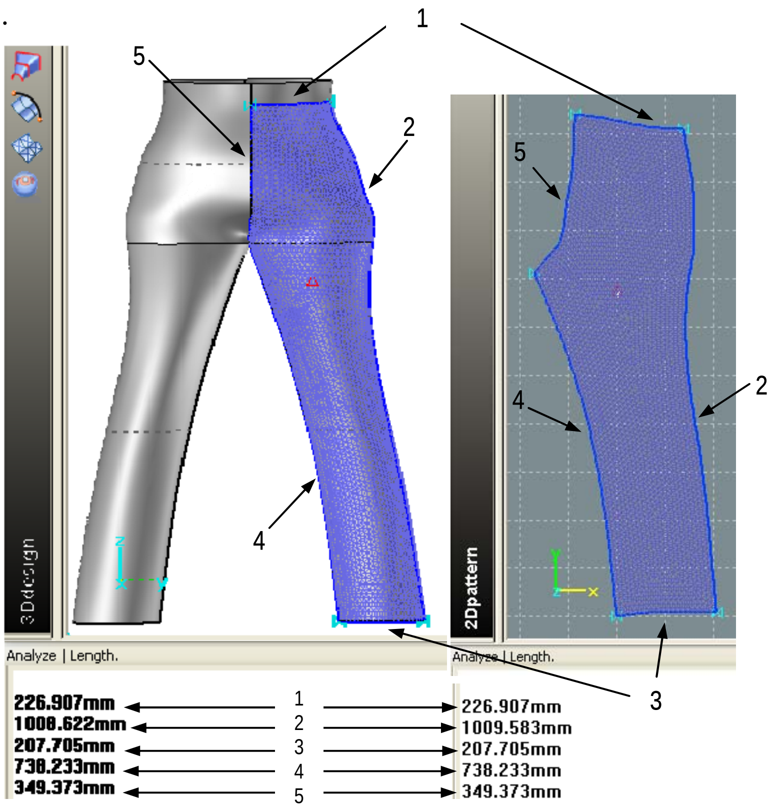


Figure 6-20 Length Analysis of Flattened Trouser Pattern of Size 90

It is noticeable in Figure 6-21 that the flattened waistband from the virtual trousers is not straight and rectangular as a traditionally drafted waistband is expected to be. This indicates that the flattened pattern pieces interpret the 3D shape of the virtual garments and will reproduce it exactly without the necessity of any darts when assembling the fabric together. However, in conventional pattern drafting the waist line and waistband are designed with straight lines (Aldrich, 1990). To match with the existing convention, flattened patterns may be required to process in a 2D system for certain modifications or an improved flattening engine may be employed.

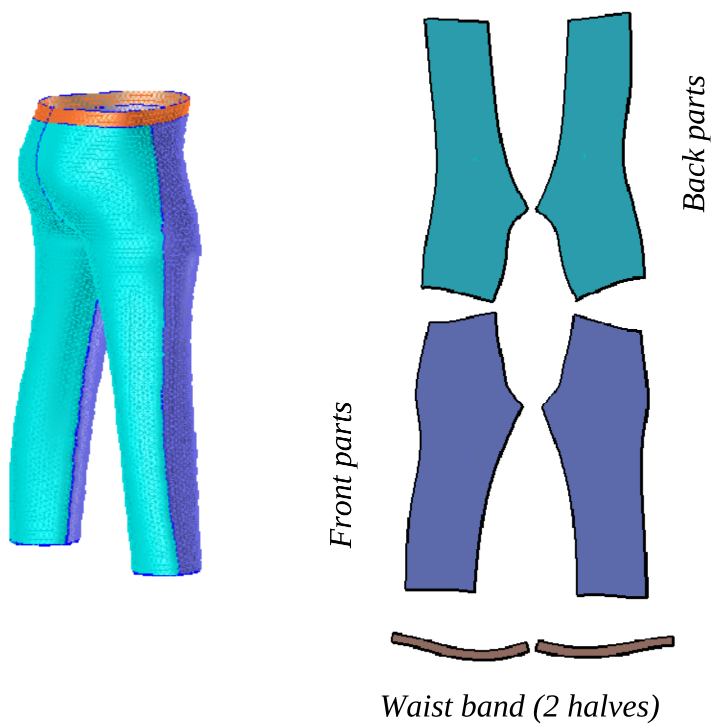


Figure 6-21 Flattened Pattern Pieces from Virtual Trouser

6.1.6 Physical Prototypes

When trialled by live models the prototypes of tee-shirts, made based on the flattened pattern pieces, of both sizes 38 and 40 resulted in manufactured garments with an acceptable overall fit on visual assessment. Especially the fit at the chest, shoulder and arm-hole areas were found to be very good, as can be seen in Figures 6-22 and 6-23. This indicated the functionality of the designated technique. Although a visual assessment could easily identify wrinkling and waviness in different areas both at the front and back parts of the prototypes during wearer trials, it does not always provide any meaningful information about the fit of a piece of clothing item and the quality of pattern pieces used to create it. Such waviness on clothing is always acceptable and cannot be avoided due to general properties of textile fabrics. For example, an M&S Blue Harbour Pure Cotton T-shirt which was on offer on the M&S website in October 2011 (M&S, n.d.) also showed waviness both at the front and at the back even after professional photographic shooting with a professional model, as can be seen in Figure 6-24.

Figure 6-22 Shirt Prototype in Size 38 trialled by One Model

Model 1: *Front, Back and Side views with different arm positions*

Model 2: *Front and Side views*

Figure 6-23 Trials of Shirt Prototype in Size 40 by Two Models

Figure 6-24 M&S Blue Harbour Pure Cotton T-shirt (M&S, n.d.)

In the case of the 3/4 length trouser prototype, general assessment of the prototype and the wearer trial also revealed that the flattened pattern pieces extracted from the trouser design developed on the 3D template were effective for use in garment manufacture. Figure 6-25 presents the wear trial of the trouser prototype by a live model.

Figure 6-25 Trial of Trouser Prototype in Size 86

6.1.7 Combining Fashion Drawing and Pattern Creation

It has been found that the virtual clothing created as a triangulated mesh surface on both the shirt and trouser templates could be visualised differently with a solid coloured surface or with different graphical features. Examples are presented in Figures 6-26 and 6-27. This facilitates fashion drawing in a 3D format and such 3D drawings and illustrations may be used for preparing different visual boards at different stages of the design process. Mood Boards which are extensively used as communication and marketing tools in the fashion industry (Cassidy, 2008) may now include more realistic 3D illustrations of clothing in respect of its actual shape and silhouette. As the virtual clothing created using this technique can also be flattened into accurately measured flat pattern pieces automatically, designers will have pattern pieces already created during the design stage. No additional effort will be needed for pattern creation. This has significant implications for the clothing industry in terms of time, manpower and cost, as both creative design and technical design parts of clothing development are combined into one.

Figure 6-26 Examples of different Print Effect on Virtual Shirt

Figure 6-27 Examples of different Check Effects on Virtual Trousers

However, it has been found that multi layer fabrics could not be visualised properly using the existing capability of the CAD system used in this work. As can be seen in Figure 6-28, the overlapping area of the left and right front panels and lapels on the front parts are not perfectly visualised. This requires an improvement in the rendering strength of the CAD system.

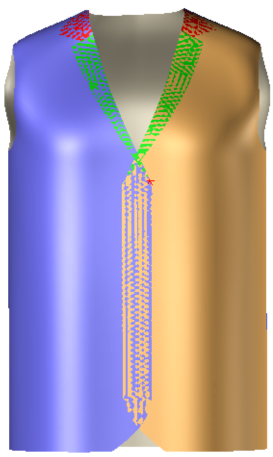


Figure 6-28 Virtual Men's Suit Jacket after Solid Colour Rendering

6.2 Development of Standard Template for Industrial Use

Although the 3D templates developed in this work have been found to be fully functional and to meet the requirements effectively, they cannot be considered as universal templates for the outerwear they represent. This is because the body scan data used as the primary input in this work do not represent any standard average body of any size group. Rather they were readily available and used for convenience. Furthermore the size databases developed for the purpose of 3D grading are also not based on the most recent anthropometric survey. However the demonstrated techniques can easily be implemented for developing standard templates for any size group of a demographic population utilising the datasets from the latest anthropometric surveys, for example SizeUK, which covers a 3D shape analysis of selected population subsets categorised by age, region, socio economic group or ethnicity (SizeUK, n.d.). Table 2-3 included in section 2.5.2 in Chapter 2 lists the recent European and American sizing surveys that have captured 3D data using body scanners and which have stored the data sets for future use. These data sets can be ready sources for finding the most suitable average 3D shapes representative of each size group of an ethnic origin for the development of standard 3D templates for outerwear.

6.3 Novel Clothing Design System

This research paves the way for developing a comprehensive 3D software suite for the clothing industry that will combine both “2D to 3D” and “3D to 2D” approaches as suggested by Okabe et al. (1992) and McCartney et al. (2000) (described in section 2.1.6) for both outerwear and bodywear. Only a few of the available clothing CAD systems, namely *3D Interactive software* from TPC (Hong Kong) and *3D Runway* from OptiTex International (Israel), include the capability of pattern flattening and this is intended only for close-fitting garments that represent less than 15% of total clothing consumption according to the Centre for the Promotion of Imports from Developing Countries (CBI) based in the Netherlands (CBI, 2008). For outerwear which represents more that 80% of total consumption, no solution has been available on the market prior to this research work. This research has demonstrated successful implementation of pattern flattening technology for outwear with the help of product-specific 3D templates. Combining this feature with the readily-available features in 3D CAD systems leads to the development of a new generation of clothing programs that will combine creative clothing design and pattern creation into a single step. An outline of such a clothing design system is presented in Figure 6-29.

The proposed CAD system will consist of the following three core modules connected through a common interface:

a) 3D design module;
b) 2D pattern module;
c) 3D drape and fit simulation and illustration module.

Each of the core modules will have several constituent components to make it fully functional. Construction of each of the core modules and the functions provided by their components are discussed in the following subsections.

6.3.1 3D Design Module

This module will be used by clothing designers to develop 3D virtual clothing with flatten-able surfaces. To be able to do its function properly, this core module will need to have the following sub-components:

a1) 3D Design platforms
  a11) 3D Outerwear Templates
  a12) Virtual Mannequin as 3D Bodywear Templates (Shared with c2);
a2) 3D Drawing and Surface Generation Tools;
a3) 3D Grading Tools;
a4) Size Database;
a5) New Size Database Creation Tools;
a6) Library of Small Parts.

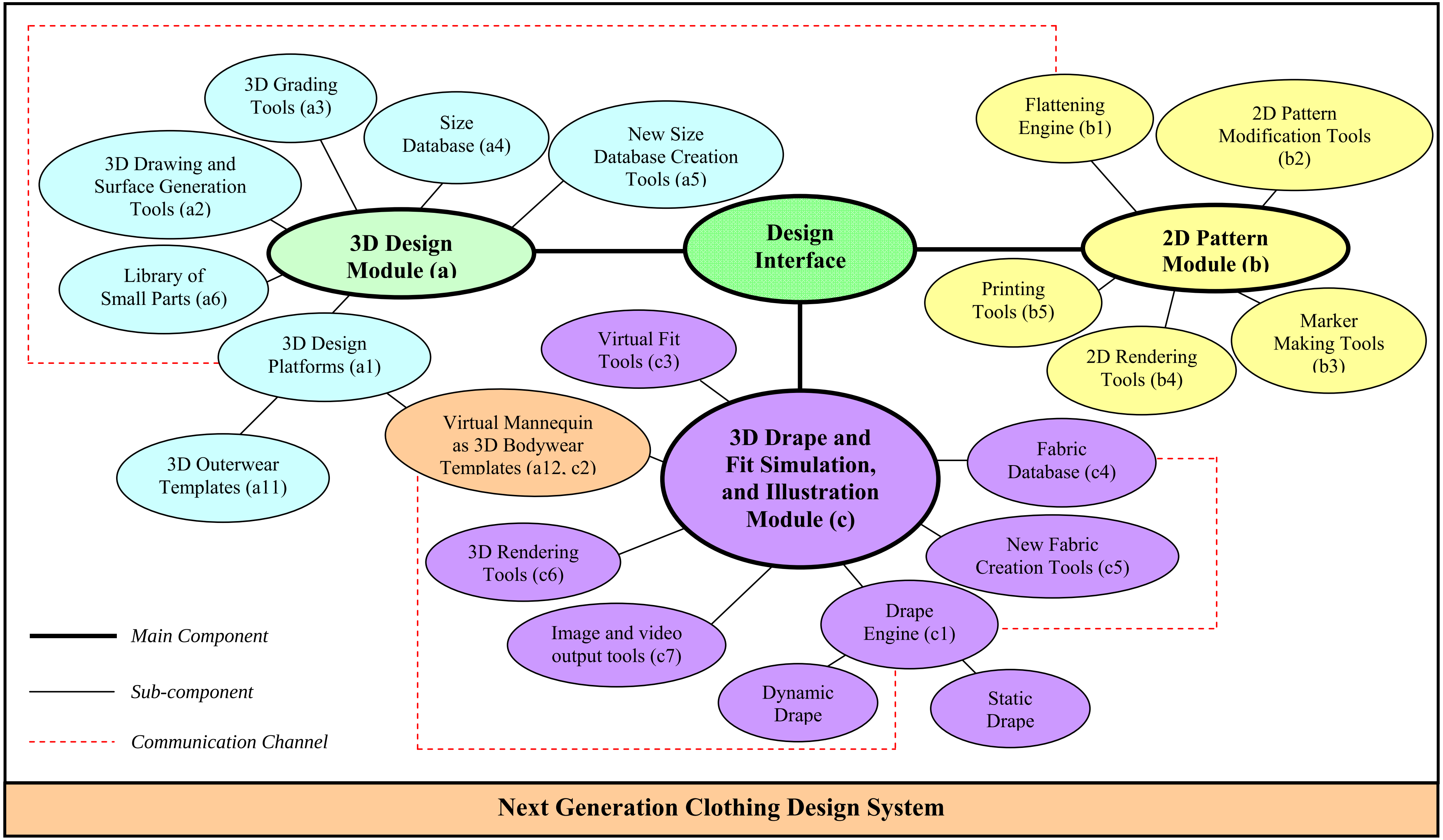


Figure 6-29 Outline of a Novel Clothing CAD System

a1) 3D Design platforms

3D design platforms will work as 3D drawing boards for the designer to create virtual clothing on them. Virtual mannequins have established uses as 3D design templates for developing virtual body wear (Hinds and McCartney, 1990; McCartney et al., 2000; Wang, Wang and Yuen, 2002; Sayem, 2004; Petrak and Rogale, 2006). Development and use of product specific outwear templates have been demonstrated in this work. Such built-in templates relevant to men's, ladies' and children's wear will form an integral part of the 3D design module of the proposed novel clothing design system.

a2) 3D Drawing and Surface Generation Tools

A set of 3D drawing and surface generation tools will be available in the 3D design module to help realise 3D clothing design on the 3D templates. For example, the 3D drawing tools and surface generation tools available in the DCTT software suite that has been used in this work may be considered. However, more customised tools for drawing standard clothing curves such as the neck curve, the armhole curves and tools to mirror curves from one side to another side to ensure the symmetry of clothing will certainly be beneficial for clothing designers. It is also suggested that the most appropriate parameters of link length and vertex angle should be set by default in the surface generation tools to avoid any heuristic approach in clothing design and to make the system more user-friendly to designers.

a3) 3D Grading Tools

In order to ensure automatic 3D grading of virtual clothing, a set of grading tools need to be made available with the 3D design module. These tools will provide a bridge between the size database and virtual clothing and will ensure required change in size and shape according to the linked size data. For example, the Excel-Linking tools available in the DCTT program can be considered.

a4) Size Database and a5) New Size Database Creation Tools

Additionally a built-in size database derived from a recent anthropometric sizing survey, for example SizeUK, will reduce the designer's workload and time involvement. At the same time, a set of tools will be required to offer creation of a new size database interactively, accepting input from a body scanner directly and merging any external database with the existing database.

a6) Library of Small Parts

A library of small parts such as collars, pockets and cuffs will be helpful for designers, especially to overcome any design limitation of the outer templates as experienced with the shirt template in this work.

6.3.2 2D Pattern Module

The function of this module will be to create 2D pattern pieces from 3D design and to prepare a pattern piece for the next steps of garment manufacture. To do this the module will be expected to have the following sub-components:

b1) Flattening Engine;
b2) 2D Pattern Modification Tools;
b3) Marker Making Tools;
b4) 2D Rendering Tools;
b5) Printing Tools.

b1) Flattening Engine

Creation of 2D pattern pieces from 3D designs will be realised with the help of an appropriate flattening engine. Development of a flattening engine for clothing patterns is described in the work of McCartney et al. (2000), Kang and Kim (2000), Wang, Wang and Yuen (2002), Petrak and Rogale (2006), Kim and Park (2007) and Fang and Ding (2008). Flattening tools are already in use in CAD systems such as 3D Runway suite (OptiTex) and DCTT (Lectra). This will make an inevitable constituent in the proposed next generation clothing CAD systems.

b2) 2D Pattern Modification Tools

To facilitate the addition of extra ease and seam allowances and to allow the designer to implement any intended changes to the flat pattern, the 2D pattern module will also require relevant pattern modification tools.

b3) Marker Making Tools, b4) 2D Rendering Tools, and b5) Printing Tools

This module is also required to offer marker marking tools and pattern printing tools to facilitate the next steps of garment manufacture. A set of 2D rendering tools will be required to visualise the marker with the artwork of the actual fabric to help the pattern positioning in special cases, for example, in case of check or stripe matching between different components of a garment.

6.3.3 3D Drape and Fit Simulation and Illustration Module

This module will include some of the features that are available in CAD systems that support "2D to 3D" visualisation of virtual clothing. The module will include the following sub-components:

c1) Drape Engine (Static and Dynamic);
c2) Resizable Virtual Mannequin for fit check
(shared with a12);
c3) Virtual Fit Checking Tools;
c4) Fabric Database;
c5) New Fabric Creation Tools;
c6) 3D Rendering Tools;
c7) Image and Video output tools.

c1) Drape Engine (Static and Dynamic)

A drape engine is available in the software programs: *Vstitcher* (Browzwear), *Accumark vstistcher* (Gerber), *Haute Couture* (PAD system), *Modaris 3D FIT* (Lectra), *efit Simulator*^{TM} (Tukatech), *3D Runway* (OptiTex) and *Vidya* (Assyst). This will be an integral part of the proposed clothing design systems as well to facilitate virtual fit check using the flattened pattern pieces from a 2D pattern module.

c2) Resizable Virtual Mannequin for fit check, and c3) Virtual Fit Checking Tools

This module will share the resizable virtual mannequins from the 3D design module to simulate and check the fit of both close-fitting and loose-fitting garments. It will be beneficial if this module were to contain a set of tools to facilitate virtual fit checking and hence will include tools for ease mapping between the body and the fabric and stress mapping for contact points of the body and the fabric of the prototype garment.

c4) Fabric Database, and c5) New Fabric Creation Tools

This module will also have a built-in fabric database which includes the mechanical properties of commonly-used fabrics as can be found in a range of existing clothing systems. There should also be facility to insert new fabric data based on mechanical properties measured by objective fabric evaluation systems such as KES and FAST.

c6) 3D Rendering Tools, and c7) Image and Video output tools

For a more realistic representation of virtual clothing, a set of 3D rendering tools should be made available within the proposed CAD system. In order to make it possible to use the created 3D illustrations and communication and marketing tools including a virtual catwalk for design presentations and for internet marketing by the designers, a set of image and video capture tools, which are not commonly incorporated into clothing CAD systems but which are already technically possible, should be included with the next generation clothing design systems proposed here.

Chapter 7: Conclusion and Recommendations

7.1 Conclusions

Unwrapping virtual clothing into flat pattern pieces offers a number of benefits to the clothing industry. If it can be implemented successfully it can merge creative clothing design and pattern creation processes together, as no extra effort is required to produce flat patterns from virtual clothing using this technology. Traditionally these two processes of clothing development are executed in two steps by two separate professionals. Combining them into a single step means not only a reduction in manpower involvement, but also a meaningful cut in product development lead time. However, in order to implement this technology in the industry, an efficient clothing CAD program package with functional 3D design platforms for both intimate wear and outerwear and a flattening module are needed to be available on the market. The virtual mannequin has been adopted as a solution for creating body-hugging garments and this has been demonstrated in number of scientific works. However it does not offer any help for the development of outerwear, which covers the lion's share of total clothing consumption. Without an efficient solution for outerwear, pattern flattening technology is not completely meaningful for the industry. This research has addressed this problem. Product-specific resizable templates as 3D design platforms for designing and flattening outerwear have been hypothesised and finally demonstrated.

Reverse engineering and geometric modelling techniques have been applied to develop two resizable 3D outerwear templates, one for men's shirts and another for men's trousers and shorts, within the extent of this research work. The resizable 3D platforms, which can work as 3D drawing boards for designers, were developed using two sets of body-scanned data as the primary input.

The functionality of both of the outer templates was tested within the environment of an available 3D CAD system. It has been found that both the shirt and trouser templates served as 3D drawing boards for the development of virtual shirts, trousers and shorts respectively. Virtual clothing developed on them could also be readily developed into 2D pattern pieces using a flattening engine.

The shirt and trouser templates have been scaled with twelve size parameters and eleven size parameters respectively and may thus be converted from one size to another using the size databases developed. This offers the opportunities for automatic grading in 3D and for the creation of a variable silhouette.

Using the resizable design platforms, it was found possible to combine fashion design and pattern creation into a single step. The virtual clothing drawn on them changed their sizes with the size change of the design platform, which ensures automatic 3D grading. Integrating such resizable design platforms into 3D clothing CAD systems will have significant implications for the clothing and fashion industries.

The process developed and demonstrated here will serve as a guideline for software developers while developing 3D design interfaces for outerwear, for both men and women, in a 3D CAD environment directed towards pattern flattening. An outline of the next generation of clothing CAD system has also been presented in the previous chapter.

Pattern flattening of outerwear through the use of the 3D design templates developed in this research will have significant implications for the clothing and fashion industry in terms of time, cost, manpower and communication. It will offer fashion designers a fully virtual environment of integrated design and pattern creation, and will provide them with an opportunity to play a dual role in the clothing development phase. However, this impact on designers might be worth researching to understand the designers' reaction to this new technology.

7.2 Recommendations

Based on the findings and outcome of this research project, the following recommendations can be made for further work in this field:

- improvement and modification of the shirt template to merge the sleeve parts with the body part and to accommodate the armhole as a size parameter;
- development of standard templates for industrial application following the demonstrated techniques;
- development of templates for ladies' outerwear following the demonstrated techniques;
- extensive functionality testing, covering the physical prototypes for all sizes with a size group and trials with live models to judge the reliability of the templates before implementation within the industry.

And the final recommendation would be to develop the next generation clothing CAD systems as outlined within the extent of this research work.

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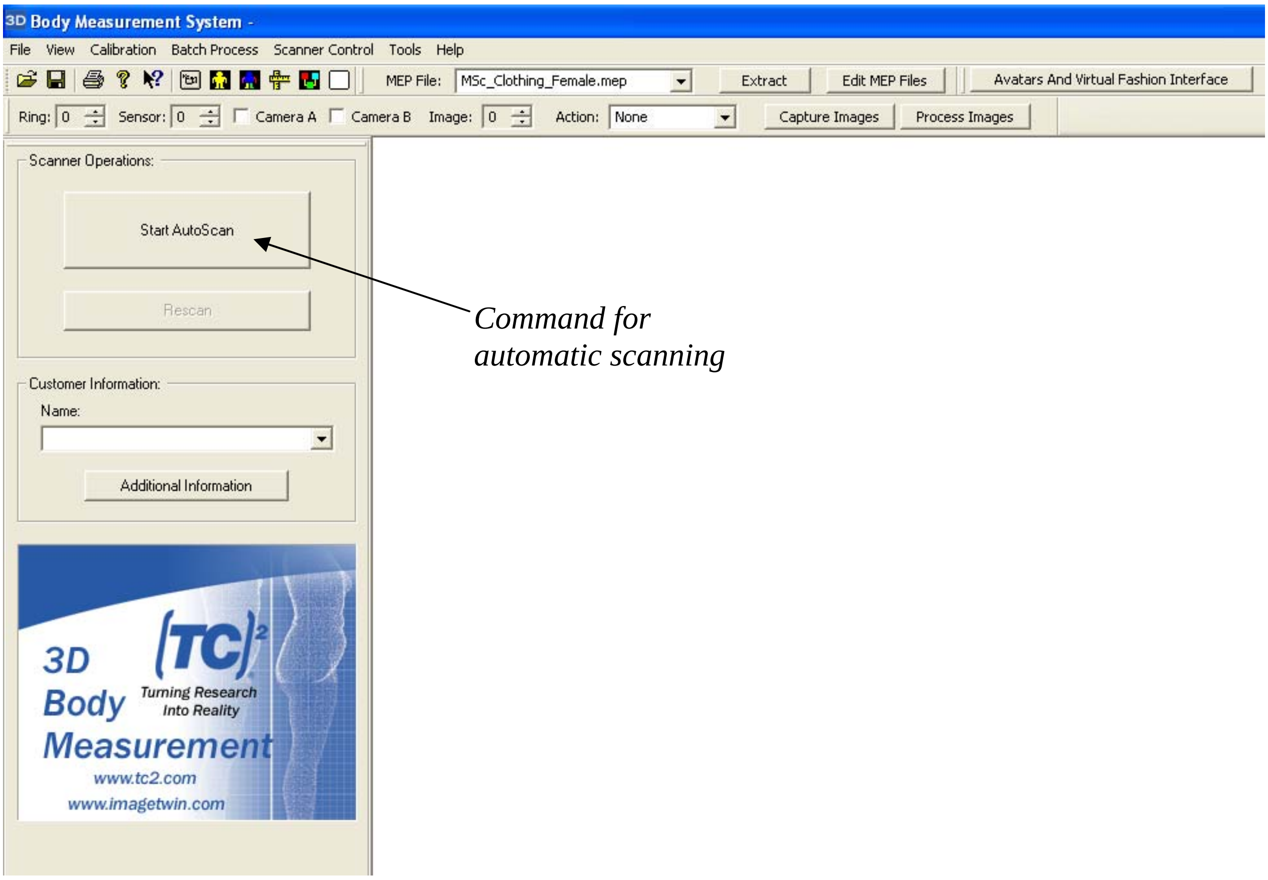
Appendix 1

1. Overview of the User Interface of the NX16® Version 7.1 Software



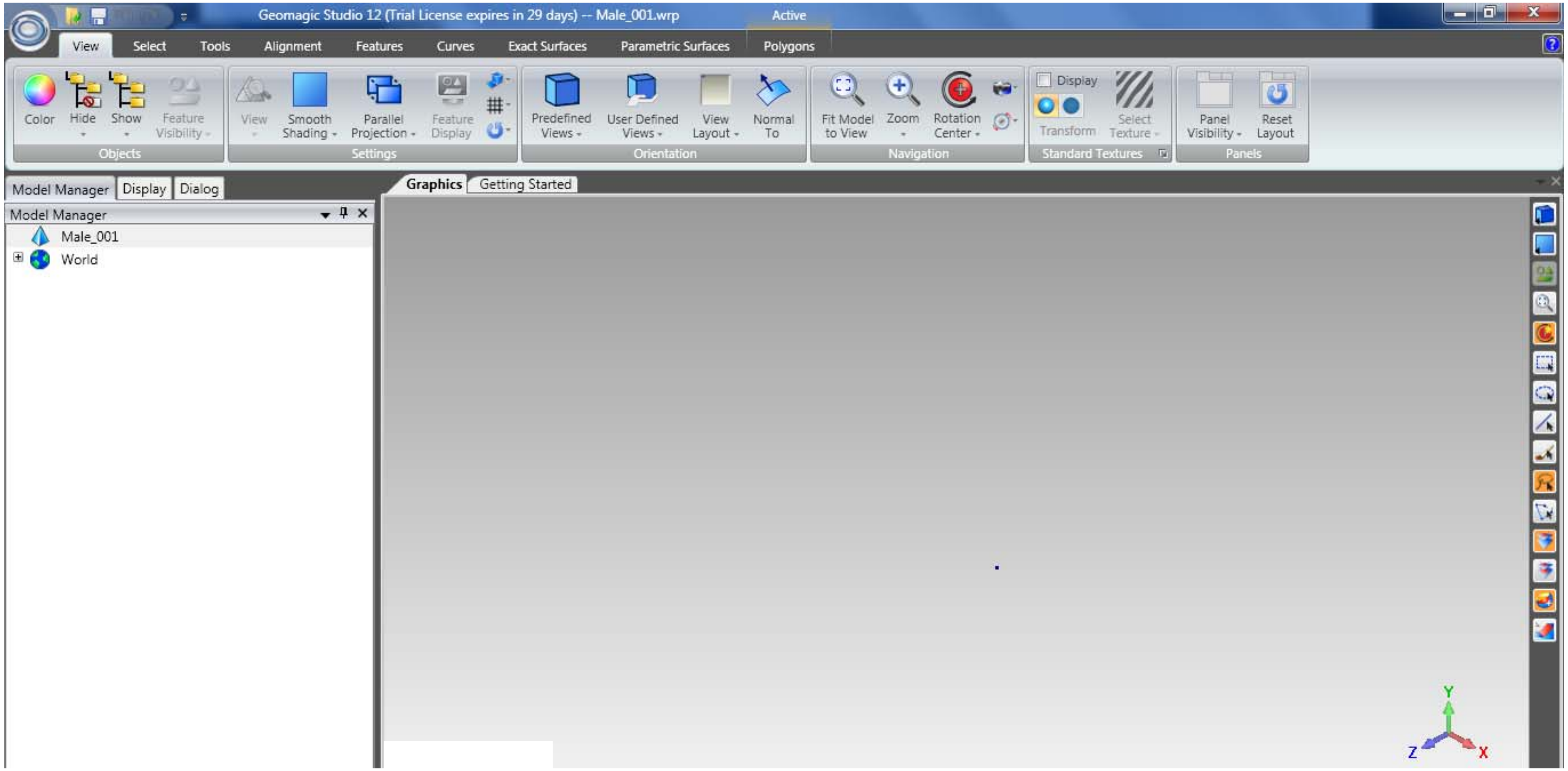
User interface of the NX16® Version 7.1

2. List of Commands used

No.	Task	Command
1	Automatic scanning	“Start Autoscan” (from side menu bar)
2	Convert “.rbd” data to “.obj” data	“Batch Process > Select File > Select Save Directory > Process Now” (from menu bar)

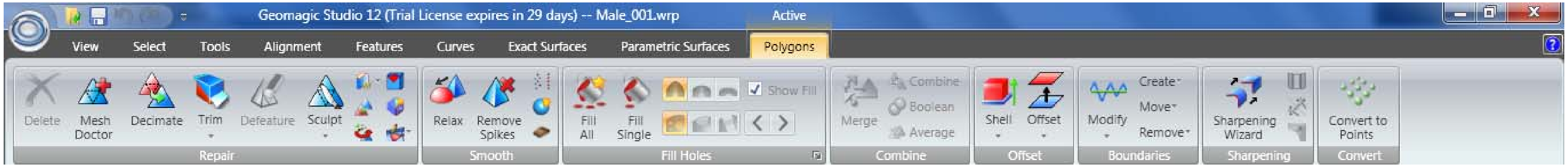
Appendix 2

1. Overview of the User Interface of the Geomagic Studio 12

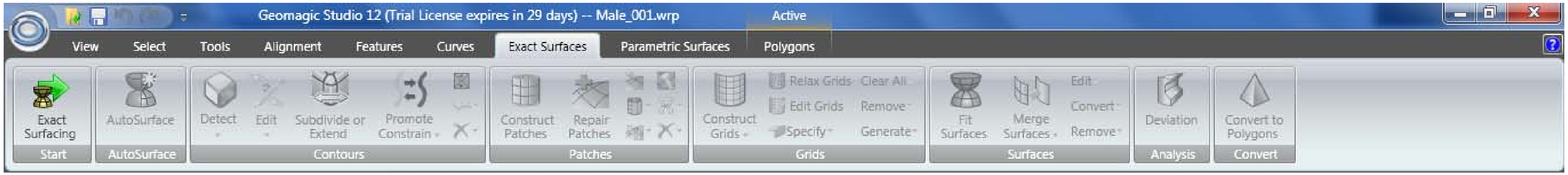


User Interface of the Geomagic Studio 12

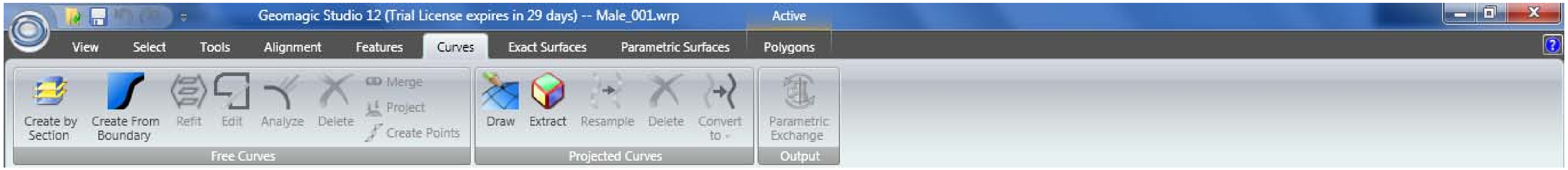
2. Sub-menus under “Polygons” menu



3. Sub-menus under “Exact Surface” menu



4. Sub-menus under “Curves” menu

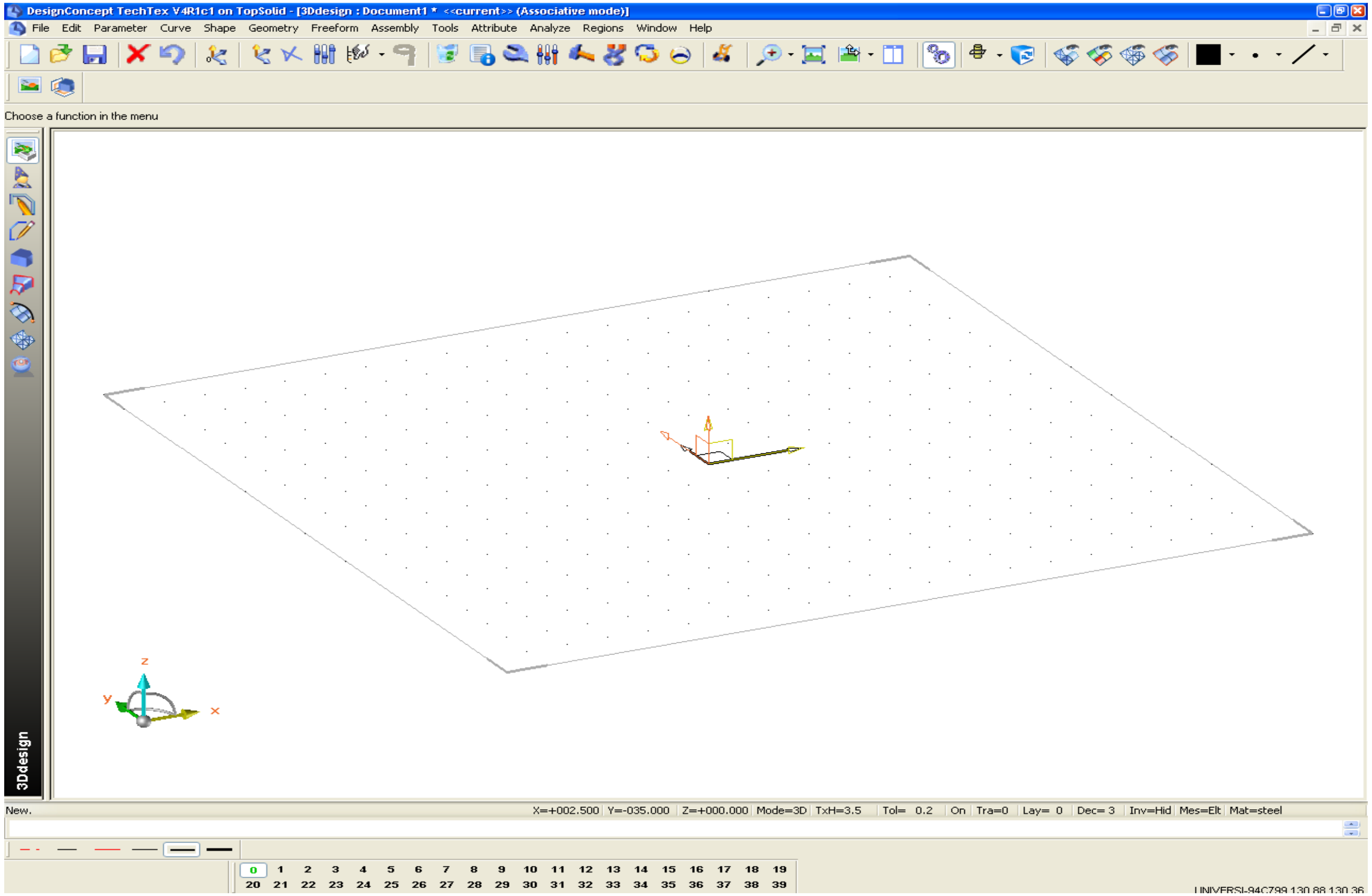


5. List of Commands used

No.	Task	Command
1	Repair imperfections of Polygonal meshes	“Polygons > Mesh Doctor” (under “Polygons” menu)
2	Generate Surface	“Exact Surfaces > Exact Surfacing > AutoSurface > Apply > OK” (under “Exact Surfaces” menu)
3	Convert NURBS model to CAD model	“ Exact Surfaces > Convert > To CAD object” (under “Exact Surfaces” menu)
4	Generate Sectional Curves	“Curves > Create by Section” (under “Curves” menu)

Appendix 3

1. 3D Design Document of DesignConcept TexTech (DCTT) Software Program



2. List of Commands used

No.	Task	Command
1	Draw Spline Curves	“Curves > Splines” (type = Interpolation, Mode = Open/Closed)
2	Halve or Divide Spline curves	“Curves > Trim > Divide”
3	Create Mirror Image	“Edit > Duplicate > Mirror”
4	Join two Curves	“Curves > Merge”
5	Define Length Parameter	“Parameter > Create” (Unit type = Length)
6	Scale Curves	“Edit > Duplicate > ‘Scaling from Point’ OR ‘Scaling with 3 Factor’)
7	Generate Surface	“Shape > Loft” (Type = SURFACE, Matching = CURVE TO CURVE, Synchronisation = PARAMETRIC)
8	Draw 3D Outlines on 3D Template	“Region > Create Region Curve > Draw”
9	Create 3D Garment Panels	“Region > Create Region > From Curves”
10	Flatten 3D Garment Panels into 2D	Step 1: Open a 2D Pattern Document, “Open > New > 2D Pattern” ; Step 2: When the 2D Pattern Document is Active, “Pattern > Create Pattern > Flatten Regions”
11	Prepare 2D Patterns	Step 1: Open a 2D Product Document, “Open > New > 2D Product”; Step 2: When 2D Product Document is Active, “Parts > Design Part > Create Seamline Part”; Step 3: “Parts > Prepare Part > Create Seam Allowance”.

12	Print 2D Pattern Pieces	“File > Print > Paper” (Mode =Portrait / Landscape, Scale = 1)
13	3D Rendering	When 2D Product Document is Active, “Patterns > Create Rendering > Create Virtual Marker”
14	3D Grading	“Parameter > Excel Link”

Appendix 4

Size Databases with Ease Allowance for Men's Tee-Shirts

1. Size Parameters with Ease Allowance for Size 37

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	37	0	0	37
Shoulder Girth	87	0	1	88
Chest girth at armpit	88	7.5	8.5	104
Chest girth at the fullest area	88	7.5	8.5	104
Waist girth	74	7.5	22.5	104
Hip girth	92	0	12	104
Upper arm girth	30	6	0	36
Arm girth on bicep	29.5	5.5	0	34.5
Forearm girth	27	3	0	30
Wrist girth	22	1	0	23
Shirt Length	76	-	-	76
Long Sleeve Length	87	-	-	87

2. Size Parameters with Ease Allowance for Size 38

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	38	0	0	38
Shoulder Girth	89	0	1	90
Chest girth at armpit	92	7.5	8.5	108
Chest girth at the fullest area	92	7.5	8.5	108
Waist girth	78	7.5	22.5	108
Hip girth	96	0	12	108
Upper arm girth	31	6	0	37
Arm girth on bicep	30.5	5	0	35.5
Forearm girth	28	3	0	31
Wrist girth	22.5	1	0	23.5
Shirt Length	78	-	-	78
Long Sleeve Length	88	-	-	88

3. Size Parameters with Ease Allowance for Size 39

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	39	0	0	39
Shoulder Girth	91	0	1	92
Chest girth at armpit	96	7.5	8.5	112
Chest girth at the fullest area	96	7.5	8.5	112
Waist girth	82	7.5	22.5	112
Hip girth	100	0	10	112
Upper arm girth	32	6	0	38
Arm girth on bicep	31.5	5	0	36.5
Forearm girth	29	3	0	32
Wrist girth	22.5	1.5	0	24
Shirt Length	80	-	-	80
Long Sleeve Length	88	-	-	88

4. Size Parameters with Ease Allowance for Size 40

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	40	0	0	40
Shoulder Girth	93	0	1	94
Chest girth at armpit	100	7.5	8.5	116
Chest girth at the fullest area	100	7.5	8.5	116
Waist girth	86	7.5	22.5	116
Hip girth	104	0	12	116
Upper arm girth	33	6	0	39
Arm girth on bicep	32.5	4.5	0	37.5
Forearm girth	30	3	0	33
Wrist girth	23	1.5	0	24.5
Shirt Length	81	-	-	81
Long Sleeve Length	89	-	-	89

5. Size Parameters with Ease Allowance for Size 41

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	41	0	0	41
Shoulder Girth	95	0	1	96
Chest girth at armpit	104	7.5	8.5	120
Chest girth at the fullest area	104	7.5	8.5	120
Waist girth	90	7.5	22.5	120
Hip girth	108	0	12	120
Upper arm girth	34	6	0	40
Arm girth on bicep	33.5	5.5	0	38.5
Forearm girth	31	3	0	34
Wrist girth	23	2	0	25
Shirt Length	81	-	-	81
Long Sleeve Length	89	-	-	89

6. Size Parameters with Ease Allowance for Size 42

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	42	0	0	42
Shoulder Girth	97	0	1	98
Chest girth at armpit	108	7.5	8.5	124
Chest girth at the fullest area	108	7.5	8.5	124
Waist girth	98	7.5	18.5	124
Hip girth	114	0	10	124
Upper arm girth	34	7	0	41
Arm girth on bicep	33	6.5	0	39.5
Forearm girth	30.5	4.5	0	35
Wrist girth	23.5	2	0	25.5
Shirt Length	82	-	-	82
Long Sleeve Length	90	-	-	90

7. Size Parameters with Ease Allowance for Size 43

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
.Neck Girth	43	0	0	43
Shoulder Girth	99	0	1	100
Chest girth at armpit	112	7.5	8.5	128
Chest girth at the fullest area	112	7.5	8.5	128
Waist girth	102	7.5	18.5	128
Hip girth	118	0	10	128
Upper arm girth	36	6	0	42
Arm girth on bicep	35.5	5	0	40.5
Forearm girth	33	3	0	36
Wrist girth	23.5	3	0	26.5
Shirt Length	82	-	-	82
Long Sleeve Length	90	-	-	90

8. Size Parameters with Ease Allowance for Size 44

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	44	0	0	44
Shoulder Girth	101	0	1	102
Chest girth at armpit	116	7.5	8.5	132
Chest girth at the fullest area	116	7.5	8.5	132
Waist girth	106	7.5	18.5	132
Hip girth	122	0	10	132
Upper arm girth	37	6	0	43
Arm girth on bicep	36.5	5	0	41.5
Forearm girth	34	3	0	37
Wrist girth	24	3	0	27
Shirt Length	82	-	-	82
Long Sleeve Length	90	-	-	90

9. Size Parameters with Ease Allowance for Size 45

Size Parameter	Measurement without ease (cm)	Functional Ease (cm)	Design Ease (cm)	Clothing measurement (cm)
Neck Girth	45	0	0	45
Shoulder Girth	103	0	1	104
Chest girth at armpit	120	7.5	8.5	136
Chest girth at the fullest area	120	7.5	8.5	136
Waist girth	110	7.5	18.5	136
Hip girth	126	0	10	136
Upper arm girth	38	6	0	44
Arm girth on bicep	37.5	5	0	42.5
Forearm girth	35	3	0	38
Wrist girth	24	3	0	27
Shirt Length	82	-	-	82
Long Sleeve Length	90	-	-	90

Appendix 5

Size Databases with Ease Allowance for Men's Easy-Fitting Trousers

1. Size Parameters with Ease Allowances for Size 74

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	74	5	0	79	39.5*
Low waist	77	5	0	82	41*
Seat	92	5	1	98	49*
Looseness control girth 1	92	5	3	100	50*
Looseness control girth 2	92	5	5	100	50*
Body rise	26.8	1	0	27.8	27.8
In seam length	78	0	0	78	78
Upper thigh at crotch point	54	7	3	64	64
Thigh	47	6	2	55	55
Knee	36	5	2	43	43
Leg girth at hem	41	-	0	41	41

*Note: * half of the final trouser measurement has been used.*

2. Size Parameters with Ease Allowances for Size 78

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	78	5	0	83	41.5*
Low waist	81	5	0	86	43*
Seat	96	5	1	102	51*
Looseness control girth 1	96	5	3	104	52*
Looseness control girth 2	96	5	5	106	53*
Body rise	27.2	1	0	28.2	28.2
In seam length	79	0	0	79	79
Upper thigh at crotch point	56	7	3	66	66
Thigh	49	6	2	57	57
Knee	37	5	2	44	44
Leg girth at hem	42	-	0	42	42

*Note: * half of the final trouser measurement has been used.*

3. Size Parameters with Ease Allowances for Size 82

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	82	5	0	87	43.5*
Low waist	85	5	0	90	45*
Seat	100	5	1	106	53*
Looseness control girth 1	100	5	3	108	54*
Looseness control girth 2	100	5	5	110	55*
Body rise	27.6	1	0	28.6	28.6
In seam length	80	0	0	80	80
Upper thigh at crotch point	58	7	3	68	68
Thigh	51	6	2	59	59
Knee	38	5	2	45	45
Leg girth at hem	43	-	0	43	43

*Note: * half of the final trouser measurement has been used.*

4. Size Parameters with Ease Allowances for Size 86

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	86	5	0	91	45.5*
Low waist	89	5	0	94	47*
Seat	104	5	1	111	55*
Looseness control girth 1	104	5	3	114	57*
Looseness control girth 2	104	5	5	118	59*
Body rise	28	1	0	29	29
In seam length	81	0	0	81	81
Upper thigh at crotch point	60	7	3	70	70
Thigh	53	6	2	61	61
Knee	39	5	2	46	46
Leg girth at hem	44	-	0	44	44

*Note: * half of the final trouser measurement has been used.*

5. Size Parameters with Ease Allowances for Size 90

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	90	5	0	95	47.5*
Low waist	93	5	0	98	49*
Seat	108	5	1	114	57*
Looseness control girth 1	108	5	3	116	58*
Looseness control girth 2	108	5	5	118	59*
Body rise	28.4	1	0	29.4	29.4
In seam length	82	0	0	82	82
Upper thigh at crotch point	62	7	3	72	72
Thigh	55	6	2	63	63
Knee	40	5	2	47	47
Leg girth at hem	45	-	0	45	45

*Note: * half of the final trouser measurement has been used.*

6. Size Parameters with Ease Allowances for Size 98

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	98	5	0	103	51.5*
Low waist	100	5	0	105	52.5*
Seat	114	5	1	120	60*
Looseness control girth 1	114	5	3	122	61*
Looseness control girth 2	114	5	5	124	62*
Body rise	28.8	1	0	29.8	29.8
In seam length	82	0	0	82	82
Upper thigh at crotch point	64	7	3	74	74
Thigh	57	6	2	65	65
Knee	41	5	2	48	48
Leg girth at hem	46	-	0	46	46

*Note: * half of the final trouser measurement has been used.*

7. Size Parameters with Ease Allowances for Size 102

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	102	5	0	107	53.5*
Low waist	104	5	0	109	54.5*
Seat	118	5	1	124	62*
Looseness control girth 1	118	5	3	126	63*
Looseness control girth 2	118	5	5	128	64*
Body rise	29.2	1	0	30.2	30.2
In seam length	82	0	0	82	82
Upper thigh at crotch point	66	7	3	76	76
Thigh	59	6	2	67	67
Knee	42	5	2	49	49
Leg girth at hem	46	-	0	46	46

*Note: * half of the final trouser measurement has been used.*

8. Size Parameters with Ease Allowances for Size 106

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	106	5	0	111	55.5*
Low waist	108	5	0	113	56.5*
Seat	122	5	1	128	64*
Looseness control girth 1	122	5	3	130	65*
Looseness control girth 2	122	5	5	132	66*
Body rise	29.6	1	0	30.6	30.6
In seam length	82	0	0	82	82
Upper thigh at crotch point	68	7	3	78	78
Thigh	61	6	2	69	69
Knee	43	5	2	50	50
Leg girth at hem	46	-	0	46	46

*Note: * half of the final trouser measurement has been used.*

9. Size Parameters with Ease Allowances for Size 110

Size Parameters	Measurements in cm	Functional Ease	Design Ease	Final Trouser Measurement	Linking Value for Scaled Curves
Waist	110	5	0	115	57.5*
Low waist	112	5	0	117	58.5*
Seat	126	5	1	132	66*
Looseness control girth 1	126	5	3	134	67*
Looseness control girth 2	126	5	5	136	68*
Body rise	30	1	0	31	31
In seam length	82	0	0	82	82
Upper thigh at crotch point	70	7	3	80	80
Thigh	63	6	2	71	71
Knee	44	5	2	51	51
Leg girth at hem	46	-	0	46	46

*Note: * half of the final trouser measurement has been used.*