Chapter 1

Literature Review

Clothing is one of the most distinctive features of human being that differs us from other creatures. The history of the cloth can be traced back to 107,000 years ago(Kittler et al. 2003; A.Toups et al. 2011). During the development of the cloth, the basic function of the cloth remains, that is to provide protection to the wearer from environment. Cloth also performs a wide range of cultural and social functions which expresses the personality, occupation, sexual differentiation, and social status of the wearer (Harms 1938).

In the world of today, with the high speed development of computer hardware and computer graphic techniques, realistic virtual character has been wildly used in film, TV and game productions. Apart from the body motion and the facial expression, same as in reality, the cloth plays a very important role in acting. In order to achieve high visual realism, many techniques have been developed in the areas such as motion capture, muscle simulation, and skin deformation, etc. However, in computer animation, virtual clothing which involves both textile engineering knowledge and artistic expertise, is considered as a challenging task. Especially for cloth modelling, current methods still require large amount of manual operation and it is a very time-consuming task in the animation production.

The cloth making techniques have been developed for hundreds years, a well developed cloth production pipeline is widely used in today's cloth manufacturing. This thesis adapts the cloth production techniques in fashion industry into the cloth modelling process in computer animation to improve the efficiency and reduce the tediousness of current cloth modelling techniques. Cloth pattern is the most common cloth design representation in the fashion industry. In order to model cloth based on cloth pattern efficiently, a general overview of the cloth pattern in fashion industry is presented in this chapter. Because the measurements acquisition for cloth making is crucial to the fit of the cloth, therefore, a detailed introduction of the research achievements in anthropometry study is presented. After that, the state of the art virtual clothing techniques are introduced. This thesis utilises geodesic to mimic the tape measuring in fashion industry for the measurements extraction from the character model and uses genetic algorithm to adjust cloth patterns automatically, therefore, finally, a brief review on geodesic algorithm and genetic algorithm is presented.

1.1 Patternmaking in Fashion Design

The construction of a complete cloth consists of several interdependent yet inseparable steps. Each step heavily affects the appearance and fit of the garment. Within these steps, patternmaking settles among the earliest few steps in the construction of a complete cloth. It is a highly skilled craft that has evolved over the centuries.

In the ancient Roman period, producing textile materials was a laborious process. Fabric was weaved using primitive looms entirely by hand. Therefore, fabric was a very expensive commodity and it was an important symbol for the social status of the wearer. In terms of structure of the cloth at that time, the cloth was mainly consisted by a set of uncut, rectangular shaped fabric pieces in order to minimize waste (Vout 1996).

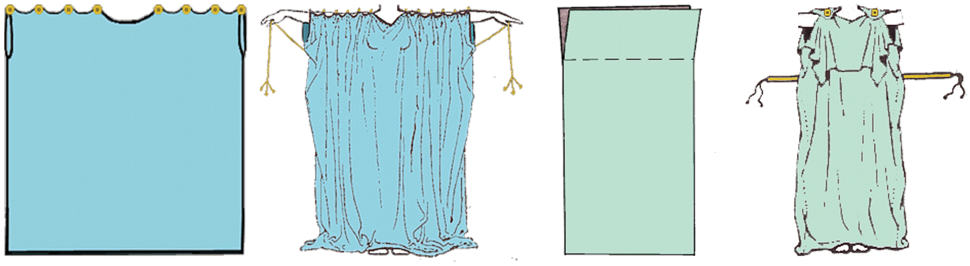

Figure 1.1: *The peplos(left) and the chiton(right) was the common cloth wear by woman in ancient Roman (McManus 2003).*

In the 15th century, the seminal art of patternmaking began. The fabric was carefully trimmed to fit the contour of the body(MacDonald 2009). The foundation of the modern fashion design was built since then. Before the industrial revolution, patternmaking is a highly respected art. During that time, tailors choicely worked with the measurements taken from their costumer to handmade cloth patterns. Only the high society are able to afford tailor made cloth. During the industrial revolution, standardization of the cloth pattern has become essential to the popularization of the massive produced cloth. However, the initial attempts to create standardized cloth pattern resulted in a little detailed cloth that is poorly fitted. After large amount of experimentation and standardization of sizing regulation, patternmaking has successfully transferred from customization to standardization(MacDonald 2009). During that time, cloth patterns are made into one size, the tailor had to grade the cloth pattern to the size that wearer was needed. Because pattern-grading requires lots of tailoring expertise and experiences, cloth pattern was not widely accepted in home sewing. At the end of 19th century, Butterick introduced the revolutionary graded cloth patterns(Butterick 1994). The effects of this idea were significant as it opens up the market of home sewing to the general public. With the advent of Butterick's pattern, not only did dressmaking become much easier, but also did the fashion became available to the general public over the world. During the WWII, with the help of the development of anthropometry, the graded pattern could fit the general public better than before. After nearly a century, patternmaking has been widely accepted by today's fashion industry(Noke 1987; Rosen 2004).

Today's patternmaking techniques mainly consist of two general categorises, patternmaking for massive production(Nugent 2008; Shoben & Ward 1987; Stecker 1996; Staff 2007), and patternmaking for custom tailoring(Margolis 1964; Cabrera & Meyers 1983; Browne 2011). The patternmeking in massive production mainly focus at the ease of distribution and standardization. This type of patternmaking techniques grade patterns into different predetermined size in order to fit most of the body size in general public. In custom tailoring, patterns are distributed as an one size design concept, the final cloth requires experienced tailor to adjust the size and shape of the cloth patterns based on the measurement taken from the customer to create fit cloth.

The research presented in this thesis brings the idea of custom tailoring into the construction of virtual cloth. Cloth are created from cloth patterns that are adjusted based on the measurements of the character. This approach allows a cloth design to be fitted onto any character.

1.2 Anthropometry

Fit is one of the essential factors that directly determines the functionality of a cloth. In order to achieve fit, measurements of the wearer's body need to be acquired. Anthropometry is the branch of human science that study the measurements of the body size, shape, mobility, flexibility and strength(Gupta & Zakaria 2014). Human body dimension, as ours personality, is largely varied among the population. Many user-centred applications require understanding of this variability. Especially for garment industry, as cloth is an object that its functionality is determined by its coverage and sealability. Both the coverage and the sealability need to be ensured by obtaining wearer's body measurements. This section will debrief the research achievements in anthropometry and introduces the method of anthropometry data acquisitions.

Human physical stature was the first topic in the anthropometry that was studied systematically. Its history can be traced back to 18th century(Tanner 1981). However, the recognition of the human body proportion is far earlier. In ancient egypt, a modular grid was often used for the preparation of human figure painting by tome painters(Pheasant & Haslegrave 2006). This modular grid consists of 18 units from the crown of the skull to the feet. Figure 1.2 demonstrates three ancient egyptian figures that have 18:11 relationship between the height of the hairline and navel(Robins & Fowler 1994). The separation of the modular grid provides a consistent point upon which a figure's proportions could be based on.

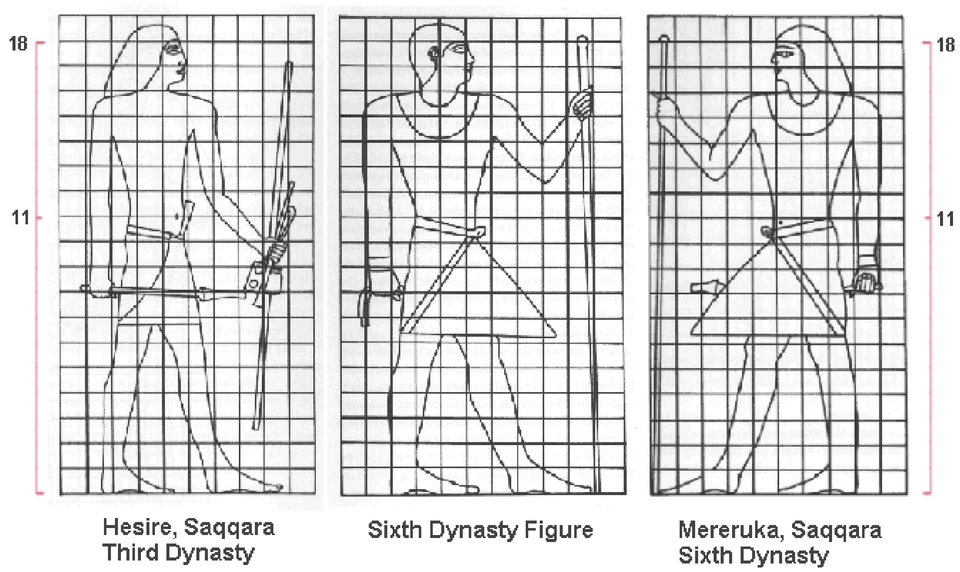

Figure 1.2: *Body proportion in ancient Egypt*

This modular system evolved initially as a drawing standard is still used today. The most detailed system of human proportions that today's anthropometry researches built on is from the Roman architectural theorist Vitruvius in 15 B.C(Selin 2008). His theory of human proportions is well known as the “well-shaped man” (Arnheim 1955), in which the height of the human stature is equal to arm span. Vitruvius also employs this human proportion as a fundamental principle in his building design as he claims that “no Temple can have a rational composition without symmetry and proportion, that is, if it has not an exact calculation of members like a well-shaped man” (Pollio et al. 1914; Frings 2002).

The most recognized visualization of Vitruvius’s human proportion is the drawing created by Leonardo da Vinci(Stemp 2006). This piece is accompanied by the nodes that are based on the theory of human body proportion developed by Vitruvius. It depicts a male figure in two superimposed postures that the arms and legs of the male are circumscribed by a cycle and a square respectively. After this piece was created, the theory of human proportion had become bound up with the “Golden ratio”. “Golden ratio” refers to the umbilicus divides of the stature of the male person in standing posture in golden section. Such that the ratio of the greater part of the stature to the whole body is equal to that of the lesser part to the greater part (Stemp 2006).

However, the study carried out by Vitruvius was based on the Roman population in 15 B.C. In the past two hundred years, anthropometry has shown that span exceeds height in 59-78% of normal adult white men (Schott 1992). The study on anthropometry was not systematically carried out until 1870. A Belgian mathematician who named Quetelet published a statistical analysis of the chest sizes of 5000 Scottish soldiers(Quetelet 2011). This was the birth of the science of anthropometry. In a very long time after the foundation of this science, anthropometric was mainly used for taxonomic or physiological studies. The development of this science accelerated during WWII powered by aircraft industry due to the needs to design better aircraft cockpits.

The measurements involved in modern anthropometry varies from field

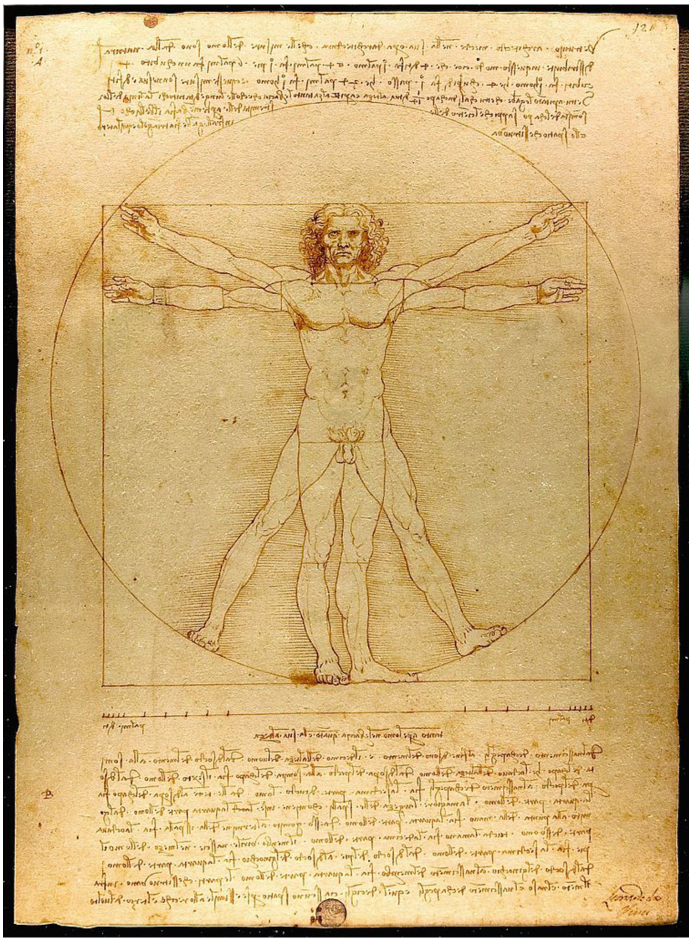

Figure 1.3: *The Vitruvian Man created by Leonardo da Vinci in 1490 (Stemp 2006)*

to field. In general, six measurements are used to describe a human stature, see Table 1.1.

Driven by the industrialization of the early 19th century, the development of standardization reached to an unpretentiously speed. In order to massively produce cloth for the general public, the grading system was introduced to the cloth making industry. This is the process that used by clothing manufacturers to produce garments in a range of predetermined sizes. Grading is a standard method of applying increases and decreases to cloth patterns to make the cloth larger or smaller(Schofield & LaBat 2005).

Height	a point-to-point vertical measurement
Breadth	a point-to-point horizontal measurement running across the body or segment
Depth	a point-to-point horizontal measurement running fore-and-aft along the body
Curvature	a point-to-point measurement following a contour
Circumference	a closed measurement that follows a body contour
Reach	a point-to-point measurement following the long axis of the arm or leg

Table 1.1: *The basic anthropometry measurements*

Generally, there are three steps involved in defining a sizing system (Schofield & LaBat 2005): Firstly divide the general population into several categories of body types with similar characteristics. Then a body measurement is selected as a primary size interval for each category, finally choose the intervals for remaining body measurements for each category. Gupta & Zakaria (2014) indicates that, one of the greatest challenges for the fashion industry is to produce cloth that fits customer properly. Therefore, for massive cloth production, anthropometry is crucial to the design of the sizing system(Norton et al. 1996; Samaras et al. 2007; Mehta 2009).

1.3 Virtual Clothing

Virtual clothing is a research topic in the field of computer graphics for a very long time. It is the generic terms of simulating clothes and clothing in computer simulated virtual environment. It reproduces both visual features and physical behaviours of textile objects in computer simulated virtual reality (Volino & Thalmann 2000). In general, today's virtual clothing methods can be classified into three types based on the core technique that used for the construction of cloth shape or its deformation. They are geometric virtual clothing, physical virtual clothing and hybrid virtual clothing.

1.3.1 Geometrical Based Virtual Clothing

Geometrical virtual clothing technique can be traced back to 1986. It was widely used for cloth modelling in the early age. Weil (1986) presented a method to generate a hanging cloth that utilises geometrical modelling techniques. The cloth was constructed by a grid consists of vertices, then the shape of cloth was generated from catenary curves between its hanging points, see Figure 1.4. This technique creates an underlying shape out of several hanging points. Then it passes through each set of these points and maps a catenary curve to the set. Finally it takes the lowest out of each overlapping set and uses it for the render. By using this method, the stationary hanging cloth can be generated efficiently, however, limited by the shape of the catenary curve, this method can only generates the hanging cloth, it cannot generates more complex shape of the cloth.

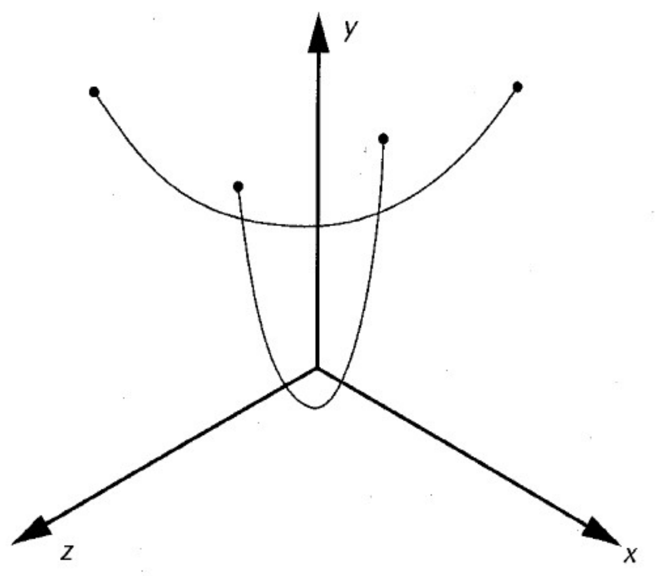

Figure 1.4: *Catenary curves for simulating hanging cloth(Weil 1986)*

T. Agui & Nakajima (1990) introduced a geometrical method for modelling a sleeve on a bending arm. The sleeve is represented by a cylinder surface consisting of a group of circular curves. The wrinkles are created by the consequence of the differences in curvature between the inner and outer part of the sleeve. This method only focused upon the simulating of bending sleeve and can only be implemented in the stationary cloth simulation.

Hinds & McCartney (1990) presented a method for interactive garments designing based on mannequins represented by bicubic B-Spline surface. The garment is represented by a group of 3D panels defined by its edges, and these are created as a surface offset from the body with various distances. later on, Hinds et al. (1991) presented a method of translate 3D pattern into 2D patterns by using the method presented by Calladine (1986).

Miller et al. (1991) introduced a geometrically deformed model. This model is developed for extracting a topologically closed geometric model from a volume data set. This method introduced a simple geometry as an initial object which is already topologically closed such as a sphere or a cube. Then based on a set of constraints, this simple object is expanded to fit the object within a volume. At the same time, the deformed object maintains its closed and non-self-intersect property. The major advantage of this method is that the sampled data are aggregated by placing geometrical relationship on the model. This allows a initial convex model to be transformed into a concave object. Since the computational cost is associated with the number of the constrain that is required during the deformation, the level of detail can be easily controlled. Later on, Thomas Stumpp (2008) extended this method into cloth modelling. This method advanced itself with a higher efficiency. According to the experiment section in this paper, their method reached linear time complexity in terms of number of the mesh vertices. However, since physical property of the cloth is related to the size of the clusters, the physical property of the cloth is determined by the topology of the cloth mesh and it cannot be controlled explicitly by the user.

Decaudin et al. (2006) presented a geometrical cloth modelling method that warps developable surfaces around the character's body in a natural manner to create visually realistic clothes. By flattening developable surfaces, it can also provides sewing patterns from 3D cloth model. This method, firstly utilises a sketch based interface to generate 3D surfaces around character body. Then, seam lines are added manually directly on those 3D surfaces. Each surface panel is enclosed by seams while all the panels are kept assembled along the seam line. Wrinkles are categorized into two types, diamond wrinkle which caused by axial compression and aligned wrinkle which caused by twisting, see Figure 1.5. All the wrinkles occurring on the cloth are generated by combining these two types of wrinkle. Due to the computational complexity of handling developable surface in implicit manner, combining these two types of wrinkle results a limited number of wrinkle variation especially for detailed wrinkle. However, this paper has addressed that this problem can be solved by adding more wrinkle types, but significant amount of computation is required to achieve such an improvement.

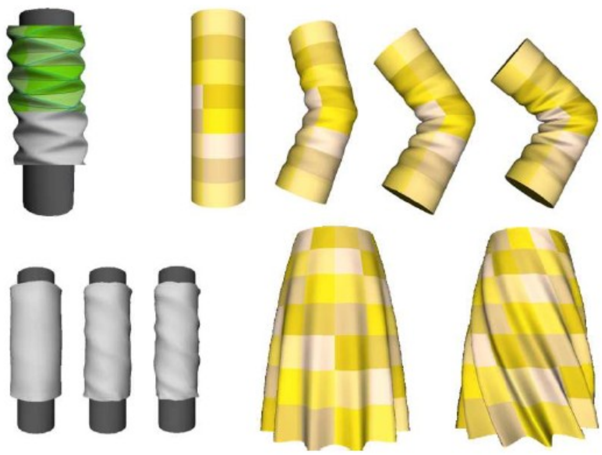

Figure 1.5: *Two wrinkle pattern presented in (Decaudin et al. 2006). First row demonstrates the diamond wrinkle pattern and its derivative. The second row is the aligned wrinkle and its derivative.*

Wang et al. (2003) introduced a feature based geometrical cloth modeling method for constructing 3D cloth from 2D sketches based on the predefined human body features. The human body features are defined based on the profiles of different body parts according to the tailoring rules in fashion industry. Based on different types of cloth such at suit and skirt, 3D cloth templates are pre-constructed. For a given human body, the 3D cloth is constructed via a three steps process, firstly, based on those pre-defined human body features, a 3D cloth template is fitted onto a human body. Then according to the 2D sketch input manually, the profiles of the 3D cloth can be specified. Finally, by interpolates the profiles on the 3D cloth template, a smooth surface is constructed via a variational subdivision scheme. For fashion designers, cloth patterns can be extracted by cutting the 3D cloth into parts and flatten them into 2D patterns. However, this method can only models certain type of cloth which shapes follows closely over body profiles. In addition, it can only generate simple cloth mesh which requires further processing to complete a detailed cloth.

Igarashi & Hughes (2002) proposed an interactive technique for putting and manipulating clothes on a 3D model. Clothes are constructed from 2D cloth patterns, and patterns are putted on 3D model by establishing proportional correspondence of free-form marks on both 3D character model and 2D patterns drawn by users. Clothes on 3D character can be manipulated with surface dragging along the body surface. This techniques can only models simple style cloth without foldings such as collar and cloth-cloth collision is ignored due to its computational costs.

Wang et al. (2009) proposed an interactive techniques to design 3D cloth directly on 3D mannequin models by using constrained contour curves and style curves. In this paper, contour curves such as silhouette curves and cross section curves are used for defining the general shape of clothes, whilst style curves such as seem lines, notch lines and dart lines are used for generating detailed 2D cloth patterns on cloth surfaces. Contour curves are extracted based on the shapes of human body and the boundaries of sub-meshes of certain style cloth. By editing contour curves, the general shape of cloth can be modified. Style lines are generated by projecting user's strokes onto 3D cloth. Patterns then can be generated by flatting mesh pieces defined by style lines. This method provides a convenient and intuitive approach to design complex cloth on 3D mannequin. However, editing contour curves and style curves requires deep knowledge in fashion design and pattern making which makes it difficult for animation artists.

(Meng et al. 2012) introduced a flexible shape control technique for resizing 3D garments automatically while preserve the shape of user-defined features on clothes. 3D clothes are modelled on a reference human body by using any type of cloth modelling techniques. The automatic cloth resizing techniques presented in this paper consisting of three steps. First, the cloth is transferred from the reference human body to the target human body by using distance constrain between the vertices on cloth and vertices on human body model. Second, B-spline curves that are created by user are used to define the shape of features on clothes and a gradient based optimization method is used to match the shape of corresponding feature curve between the cloth on reference human model and the cloth on target human model. Lastly, interpolation between feature curves on cloth for target human body are performed to form a smooth shape transaction. Because feature curves are defined by user on each cloth modelled for target human bodies, inconsistent user input can be heavily affected the preservation of cloth features.

Brouet et al. (2012) proposed an automatic method for cloth transferring between characters with different body shapes. This method fits a cloth onto a different character by adjusting the 3D cloth directly and patterns are extracted after the 3D cloth is fitted to the new character. The 3D cloth adjusting process is performed by combining the proportional scaling method with a constrained gradient based optimization process. The constrains are defined by associating the user selected point on the cloth mesh with a pair of points on the relevant bone and character skin. The distances between the selected vertices on cloth mesh to their associated point pairs are used as the parameters of the optimization. The optimization is performed by moving each vertex of the cloth mesh on its tangent space to minimize the distance changes. After 3D cloth is fitted onto the new character, the cloth patterns are extracted by using surface flattening method.

(Sheffer et al. 2005). Because the constrains of the optimization is defined by user and the selected reference points are varies on the different character model, the convergence of the optimization can be heavily affected by the user inputs. This method requires cross-parametrization between source and target models, the fit of the cloth can also be affected by the accuracy of the parametrization. Moreover, extracting the resized 2D cloth patterns requires extra computation and the distortion of the pattern shape can also be introduced by the surface flattening process.

(Turquin et al. 2007) introduced a sketch based interface for modelling 3D cloth on virtual characters. The goal of this paper is to provide an intuitive method which models cloth on 3D character based on the stocks draw by users, to be more specific, sketches of a cloth worn by a mannequin. The user drawn sketch defines the shape of the cloth, wrinkle details and how the cloth is worn by virtual character. Distances between stocks and mannequin are used to create a distance field which further to be used for cloth mesh generation. This interface to targeted for non-experienced users therefore, it can only models simple style single layer clothes.

(Umetani et al. 2011) proposed an interactive tool for cloth design that enables bidirectional editing between 2D patterns and 3D cloth. In order to maintain synchronization between 2D and 3D prospective, topology of 2D cloth pattern and its corresponding 3D cloth piece is identical and updated simultaneously by user input.

(Yu et al. 2012) proposed a sketch based interactive cloth modelling approach for dressing 3D virtual character. 3D clothes are modelled by sketching cloth contours around the character body. Key body features such as extreme points or girth of human body are used as constraints during the construction of clothes. This method provides an intuit way to model 3D clothes for artist. However, the key body features are defined based on shape similarity of human body, therefore, it is not suitable for modelling outfits for animation characters due to their various body shapes and proportions.

Geometrical based virtual clothing methods construct and edit 3D cloth shapes effectively. However, cloth is a soft object which many of its material feature can only be see when it is moving. Due to computational complexity for mimicking dynamic behaviours

Geometrical based cloth modelling method may be fast on generating the static cloth shape, but cloth is a soft object whose shape is closely associated with the shape of body underneath. The physical based simulation can generates the shape of the cloth easily and reproduce the kinetics property of textile very well.

1.3.2 Physical Based Virtual Clothing

For physical based virtual clothing methods, cloth is represented by a set of particles that are inter-connected to each other by springs. This representation replicates the behaviour of the soft flexible object such as fabric. In general, there are two types of models for the physical based cloth modelling technique, energy-based techniques(Terzopoulos et al. 1987) and the force-based techniques(Volino & Magnenat-Thalmann 2005). Energy-based model calculate the total energy of the cloth using a set of energy equations. Those equations determine the shape of the cloth by moving the particles in order to achieve a minimum energy state. This type of method is widely used in static simulations. Because the energy model is based on the kinematic theory in which the shapes are compositions of geometrically or algebraically defined primitives, and it does not interact with each other or with external forces. For this reason, the Force-based technique has been brought in to virtual clothing in order to describe the reaction of the cloth to the external forces. This type of techniques usually use differential equations to represent the force among each particle and perform a numerical integration to solve the differential equation and locates the position of each particle at every time step. This type of methods is normally used in dynamic cloth simulation.

Terzopoulos et al. (1987) introduced a method utilises the physically-based model to construct the shape of a cloth object. Their method is based on the elasticity theory to describe the shape and motion of the deformable materials. It also has the ability to interact with other physically-based models. The simulation model introduced in this paper is based on the simplifications of elasticity theory to deformable curves, surfaces, and solid objects. It has the ability to generate static shapes by simulating their physical properties such as tension and rigidity (Figure 1.6). Moreover, by bring the physical properties such as mass and damping in to the physical simulation, the dynamic of objects can be simulated. *"The simulation involves numerically solving the partial differential equation, govern the evolving shape of the deformable object and its motion through space."* (Terzopoulos et al. 1987). However, it is very time consuming for solving the energy equation for a complex object, limited by the computational power, this method can only simulates the interaction between simple shaped objects.

Volino & Magnenat-Thalmann (2005) introduced a general mechanical model for cloth simulation. Because the mass-spring system cannot represents the anisotropic nonlinear mechanical behaviour which often appears on the fabric, This model utilises an accurate particle system for dynamic sim-

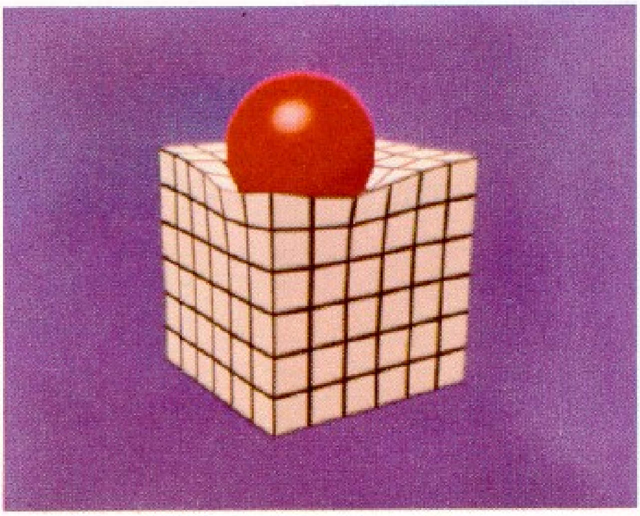

Figure 1.6: *The simulation result presented in (Terzopoulos et al. 1987), this method established the foundation of the modern energy-based cloth simulation method.*

ulation instead of mass-spring system. A triangle face of the cloth mesh is described by three 2D coordinates correspond to three mechanical properties, weft, warp elongation and shear. These coordinates describes the location of the triangle's vertices on the weft-warp coordinate system that defined by the directions U and V with an arbitrary origin, see Figure 1.7. This particle system is able to simulate the anisotropic nonlinear mechanical behaviour of a cloth object by using polynomial spline approximations of the strain-stress curves. Furthermore, the aforementioned three mechanical properties are physically measured from real cloth piece using Kawabata Evaluation System (KES) and the SiroFAST method.

Volino et al. (2009) proposed a simulation model for the large deformations of textile. It can generates the nonlinear tensile behaviour of textile with accuracy and robustness meanwhile the process of the simulation remains simple. Differing from the majority of the existing cloth simulation systems, this model uses accurate strain-stress curves to represent the weft, warp and

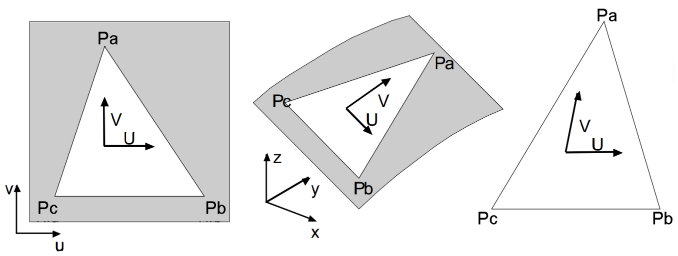

Figure 1.7: *A triangle face of cloth surface defined on the 2D cloth surface(left). The deformed triangle in 3D space(middle). The deformation of the weft-warp coordinate system of this triangle face(right).*

shear tensile behaviour. This model also includes the elasticity and viscosity which makes it suitable for dynamic motion simulation. Most importantly, the computation involved in this method is not much more than mass-spring model but offers a significantly more accurate result.

Chen & Tang (2010) introduced a method for simulating inextensible cloth subjected to a conservative force (e.g., the gravity) and collision-free requirement. This paper points out that for a piece of cloth, its stretch resistance and compression resistance are many times larger than its bend resistance. Therefore, the simulated cloth can be considered as an inextensible object. However, traditional physically-based cloth algorithm cannot preform correctly if some of the stiffness coefficients are set close to infinite. Thus they provide a method such that the physical-based simulation process is transferred into a deformation process of an initial developable mesh surface to a final mesh surface. Their method deforms cloth mesh by using energy minimization. Gauss-Newton iteration is used for the minimization of the energy function. However, this method can only handles the conservative force, it cannot handles non-conservative force such as friction. The other crux is that since it uses energy minimization to determine the final shape of the cloth object, the simulated cloth object can only achieve to one steady states therefore it is not suitable for dynamic use.

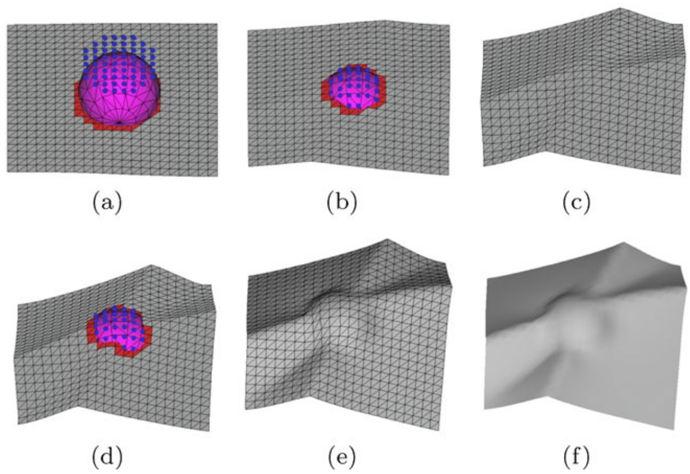

Figure 1.8: *blue points are the dynamic anchor points, (a), (b), and (d) are three intermediate states in sequence.The number of the dynamic anchor points are reduced gradually; (c) and (e) are the two sequent intermediate states where the potential energy of the mesh is lowered gradually. (f) is the final state where the potential energy reach to the minimum (Müller & Chentanez 2010)*

Physical based virtual clothing method calculates the inter-force amongst each vertex. The number of the vertices which construct the cloth directly influences the detail and performance of the simulation. Therefore, in order to produce fine detail results, the resolution of the cloth mesh must stays high which leads to a very heavy calculation. Moreover, the parameters of the differential equation used for representing the cloth object is difficult to obtain. Thus it has been mainly used in off-line high accrue simulation such as garment industry and off-line film production. In game industry, limited by the heavy computation of the physical based virtual clothing methods, the detail of the cloth is largely constrained.

1.3.3 Hybrid Virtual Clothing

Hybrid virtual clothing method combines both physical simulation method and other types of deformation methods together such as data-driven method or geometrical method in order to compensate the shortcomings of each techniques to produce a fine result meanwhile minimize the calculation.

In order to reduce the computation complexity of the physical cloth simulation techniques, Rudomin (1990) presented a method uses geometrical approximation to reduce the computation time of physical based virtual clothing method introduced by Terzopoulos et al. (1987). Later on, Kunii & Gotoda (1990); Tsopelas (1991) proposed a series of hybrid virtual clothing methods that map geometrical modelled fine wrinkle details onto the physical simulated cloth mesh in order to avoid the heavy computation for simulating the high resolution mesh. Hadap et al. (1999) introduced a texture based wrinkle modelling method for cloth simulation. This method generates the deformation detail based on the bump map that is created by user on a physical simulated coarse cloth object. However, because there can be a limited number of the pre-defined shape details or bump maps created by user, the variety of the deformation is consequently limited.

Data-driven method is widely used in combining with physical based simulation method to improve the efficiency of the cloth simulation. Cutler et al. (2005) introduced a kinematic method for generating wrinkles on cloth for CG characters. Winkles are created by artists using the geometric sculpture software and are stored into the database. The final cloth deformation details are generated by matching the similar stretch distribution of current cloth to the referencing posture of the character. However, the similarity between the reference posture and the coarse physical simulated cloth only exists on the tight fit cloth, the wrinkle database can not be used to generate shape detail on the loose fit cloth. Popa et al. (2009) introduced a data-driven method for generating the fine folds on the captured cloth model. In this method, the shape and the position of the wrinkle are captured from video footage based on the wrinkle's distinguishing shape characteristics, and the wrinkles are created by using stretch-minimizing deformation, which produces believable wrinkle shapes. However, the details of the captured wrinkles are limited by the resolution of cloth mesh therefore, significant amount of detail can be lost during the capturing process.

Feng et al. (2010) introduced a hybrid method which can provide high-quality dynamic folds and wrinkle for cloth simulation while still maintaining real-time ability. This method captures the relationship between the two different resolutions of mesh by using data-driven model. Then this relationship is used to transforming the lower quality deformation of the lower resolution mesh through a mid-scale deformation transformation onto the higher resolution mesh with the fine details added on. In the animation pipeline which they developed, during each time step, it starts with the physical simulation for the low-resolution mesh. After that, the deformation transformation and collision detection is executed. In this step, two stages of nonlinear mapping are used to generate the deformation of high-resolution mesh. At the first stage, the deformation for the mesh with the lowest resolution is mapped onto a mid-resolution object which using proxy bone to represents a local region on the high-resolution cloth object, and then the deformation of the proxy bones are mapped onto the high resolution to create the final fine-scale deformation. Collision detection is also a critical and time-consuming process during cloth simulation. In this paper, they proposed a method of using the proxy bones originally for the mid-scale cloth deformation to represents the high-resolution cloth object to interact with the model of character. The bounding volume is attached to every proxy bone which represents a small area on the cloth object. When the character moves, instead of calculating the collision between each mesh triangles of the cloth and body model, they can calculate the collision between each proxy bone. Although the accuracy of collision handing is slightly reduced, the computation time for the collision test are reduced significantly. Although the efficiency has been improved significantly, like other data-driven method, it requires a time consuming pre-simulation to gain the training data. Moreover this method cannot handle the self-collision of cloth.

The hybrid method combines different modelling and simulation techniques into one package to solve the problems of virtual cloth construction. In general, other type of virtual clothing methods are used to overcome the shortcomings of the expensive computation of the physical virtual clothing method in order to provide a more effective and efficient solution for the virtual clothing. Because other type of techniques such as geometrical cloth modelling method or data-driven cloth simulation method usually compromises the physical simulation accuracy, it is often used in the area which focuses on the visual realism more than physical accuracy, such as computer animation.

1.4 Geodesics

The standard posture used for modelling character differs from person to person. Traditional anthropomorphic data acquisition method requires character to stay in a standard posture in order to extract the correct measurement data. Therefore, applying traditional anthropomorphic measuring method to the same character in different posture will result different measurements. And the cloth that is adjusted based on those measurements will be adjusted into different sizes. This will cause the ill-fit of the modelled cloth. This thesis utilises the geodesic to mimic the tape measuring process in tailoring for the measurements extraction from different characters in different postures. Geodesics are usually defined as the locally shortest path between two points on a curved space. Geodesic computation is a common operation in computer aided design, machine learning, medical image analysis and computer animation. Throughout years of research, many algorithms have been developed for various applications, such as surface-based brain flattening (Bartesaghi & Sapiro 2001; Wandell et al. 2000), mesh refining (Peyré & Cohen 2006), mesh segmentation (Katz & Tal 2003) and terrain navigation (Aleksandrov et al. 2005).

Dijkstra (1959) was the first to address the problem of "single source all destination shortest path" problem on a directed non-negative weighted graph. Early works of geodesic computation mainly focused on the convex polyhedrons. Sharir & Schorr (1984) extend the Dijkstra's(Dijkstra 1959) algorithm into three dimension space, with a time complexity $O(n^3logn)$. Later on,an exact solution of geodesics on a convex polyhedral surface was developed by Schreiber & Sharir (2006), with a reduced complexity of $O(n\log n)$.

For non-convex polyhedrons, a challenging issue is that, a geodesic path may go through the hyperbolic vertices of a polyhedron. Based on the definition of geodesic proposed by Mitchell et al. (1987a), a geodesic path on the planner forms a straight line. However, when flatten the face surround to a hyperbolic vertex, one edge will appear twice in two different edge sequences since these two edge sequences are all locally shortest around this hyperbolic vertex but not necessarily shortest in other local area, the computational result may not be correct.

In order to handle this problem, Mitchell et al. (1987b) (MMP algorithm) extended Dijkstras algorithm(Dijkstra 1959) and introduced the technique of "continuous Dijkstra" that propagates the distance information from the source outward in a Dijkstra-like manner. The "continuous Dijkstra" propagation performs as follows. Each edge is partitioned into several sections called "window", each window carries distance information through out the propagation. MMP algorithm costs $O(n^2\log n)$ time to solve the "Single Source All Destinations" problem. Surazhsky et al. (2005) implemented MMP algorithm and furthermore, they extend the original MMP algorithm(Mitchell et al. 1987b) to a bounded error approximation algorithm note as MMP approximate algorithm. The time complexity of the MMP approximate algorithm has been improved to $O(n(log)n)$(Surazhsky et al. 2005).

The other popular approximation algorithm is the fast marching method (FMM) (Kimmel & Sethian 1998). This method involves solving a discrete version of the Eikonal equation over a regular grid, with the cost of $O(n\text{log}n)$. However, the uniformity of the grid highly affects the approximation error. Therefore, performing FMM on an irregular and skinny triangulated grid will leads to significant high error. Bose et al. (2011) points out that the approximation error of FMM is unbounded.

Chen & Han (1990)(CH algorithm) provides an exact solution to the geodesic problem based on a key observation of "one angle one split" principle with time complexity of $O(n^2)$. This method consists of a two parts. In the first part, the shortest path from a given source to each vertex on the mesh is computed and a set of windows is defined on each edge. Each window contains the information about the shortest path from the given source point to points on the current window. In the second part, windows are used to compute the decomposition of the surface and the shortest path to any destination point on the polyhedral surface can be calculated. However special case needs to be dealt with in the circumstance of a geodesic passes through a hyperbolic vertex because the planer unfolding to this type of vertex can be self-overlapped.

Xin & Wang (2009)(Improved CH algorithm) discovers that in CH algorithm, many windows are unnecessary for the propagation. Therefore, their method improved the efficiency of the algorithm by introducing less windows during the propagation. Although the asymptotic time complexity is $O(n^2(log)n)$, according to the numerical experiments, the Improved CH algorithm show great advantage over CH algorithm and MMP algorithm in terms of computational time costs.

The aforementioned algorithms were developed specific for geodesic computation on polyhedron. Because "Continues Dijkstra" propagation method are used for propagating geodesic information outwards, the connectivity among the vertices is necessary. Therefore, they cannot handle the geodesic computation on scattered point cloud data. Moreover, the current geodesic algorithm usually requires "backtracing" method to retrieve the complete geodesic path information, it consumes large amount of time on the high resolution model.

For the geodesic computation on point cloud data, since there is no connectivity among the sampling point and the connectivity is the fundamental requirement for the propagation based method such as MMP (Mitchell et al. 1987b; Surazhsky et al. 2005), CH/ICH (Chen & Han 1990; Xin & Wang 2009) and FMM (Kimmel & Sethian 1998), The approximate graph need to be construct in order to form the connectivity among the sampling points. For instance, Mémoli & Sapiro (2001) extends the FMM to be able to perform on point cloud data, where the resulting geodesic is an approximation over a coarse grid on the point cloud surface. Hofer & Pottmann (2004) employed moving least squares method to constrain the discrete geodesic curves onto the point cloud surface.

Ruggeri et al. (2006); Pottmann et al. (2010) proposed an approximate geodesic method on point set surface that employs an energy-minimization function to calculate geodesics. The initial curves are created by Dijkstras algorithm(Dijkstra 1959). Then all the initial curves are refined by performing energy minimization function to form the resulting linear approximation of the geodesics. Because the energy minimization consumes large amount of time, this method is not suitable for the multiple geodesic computation.

Calculating geodesics is a very time consuming process, the reviewed researches are mainly focus at improving the efficiency of the geodesic computation while maintaining the computational accuracy. However, because high resolution character model bas become more and more popular in computer animation, the current algorithms still consume large amount time to calculate geodesics on the high resolution model. Moreover, although technique such as fast marching method(Kimmel & Sethian 1998) is proposed to reduce the time complexity of the computation, its accuracy varies among the different character models with different topology.

1.5 Genetic Algorithm

Modelling cloth from cloth patterns for a character requires each pattern to be adjusted individually. During the pattern adjustment, several criteria need to be satisfied in order to fit the cloth to the character and preserve the design of the cloth. In this thesis, pattern adjustment is considered as an optimization process that has multiple objectives. For optimization algorithms, genetic algorithm dwarfs others by its simplicity and efficiency.

In nature, individuals that suits the environment best survive. The ability of adapt to the changing environment is curial for the survival of individuals. Genetic algorithm are inspired by such mechanisms of evolution and natural selection in real world(Srinivas & Patnaik 1994). The pioneering book of Holland (1992) demonstrated wide range of problems that can be solved by using evolutionary process in a highly parallel manner. The process utilise the concept of evolution is called genetic algorithm(Koza 1995). Now a days, after decades of research, genetic algorithm has become a practical and robust optimization method that can solve wide range of problem in real world.

In general, the genetic algorithm transforms a set of individuals named population into a new generation by using Darwin's principle of reproduction and survival of the fittest(Holland 1992). Each individual in the population represents a possible solution of the given problem and every individual is associated with an fitness value that evaluates its performance to the given problem. During the process of the transformation, genetic operations are performed such as crossover(mate), mutation and selection in order to explore the new area on the cost surface. For every individual that is newly generated, a fitness value is assigned to it. This entire process is performed iteratively till the best solution is found or the evolution limitation has been reached.

There are two types of optimization based on the number of the objectives of the given problem, single-objective optimization and multi-objective optimization. For single-objective optimization, finding a single best solution is the purpose of the optimization. This method has been studied intensively for decades(Srinivas & Patnaik 1994; Koza 1995). However, many real-world problems can not be described by a single objective, moreover, in many cases, the optimization requires simultaneous optimization for multiple competing or conflicting objectives. Therefore, for multi-objective optimization, the best solution usually does not exist, instead, a group of "good" solutions are generated to form "pareto front"(Pareto 1906). Multi-objective genetic algorithm is designed specific for such type of problems.

Schaffer (1985) introduced vector evaluated genetic algorithm(VEGA) for solving multi-objective optimization problem. This algorithm is an extension of simple genetic algorithm(SGA)(Schaffer 1985). This algorithm modifies the selection operator of SGA so that at every generation, a subpopulation are selected based on each objective in turn. Let K be the number of individuals in each sub-population and N be the number of the whole population. Within each sub-population, N/K number of individuals are selected and shuffled together to form a new generation. Due to the linear combination of all objectives during the evolution process, this algorithm cannot form pareto front on the concave cost surface.

Ishibuchi & Murata (1996) proposed a weighted-sum approach for multi-objective optimization. The randomly generated weight is assigned to each objective for each individual. Crossover operator selects individuals from dominated set according to the weights of the individual to generate offspring. This method provides an approach that is highly effective for generating a strongly non-dominated solution. However, the setting for the weights can be difficult because each weight directly determines the scale of the objective. Inappropriate setting for the weights can leads to the failure of the form of pareto front. Moreover, this method cannot generates pareto optimal solutions for non-convex searching space.

Horn et al. (1994, 1993) proposed a method that based on the pareto domination tournament selection and equivalence class sharing(NPGA)(Horn et al. 1994). During the selection, a random number of individuals are selected into the comparison set, then two random individuals are compared against the comparison set for domination, If one is dominated by the comparison set and the other is not, the dominating individual is selected for crossover. If neither or both individuals are dominated by the comparison set, the equivalence class sharing is performed. During this process, the individual that has the least number of neighbours with in the niche radius(Shir & Bäck 2006) is considered "better fits". This method only performs the pareto selection to a part of the population, therefore, high efficiency can be achieved and the pareto front can be well kept throughout large amount of generations. However, because the selection only be performed on a part of the population, the quality of the convergence is highly depends the choice of the niche radius and the number of individuals in the comparison set.

Zitzler (1999); Zitzler & Thiele (1999) proposed a method(SPEA) that combines the concept of elitism and non domination. For each generation, an external population which consisted by a set of non-dominated individuals that are selected since the initial population is kept. The number of the dominated solutions determines the fitness value for each individual of current population. In general, if an individual dominates more in terms of objectives over other individuals, the higher fitness value will be assigned to the dominating individual. The external population is then updated after fitness value has been assigned to the entire population. If an individual is not dominated by both current population and external population, it is added into the external population and all the individuals that are dominated by the added one are removed from the external population. However, because individuals that are dominated by the same external population have identical fitness values. When external population only has one individual, this algorithm becomes a random search algorithm.

Knowles & Corne (1999) introduced the pareto archived evolution strategy(PAES). This method starts with a random solution of the multi-objective optimization problem. Then, this solution is mutated by a normally distributed probability function that has zero mean and constant mutation strength. The generated offspring is compared with the original solution and the one with better fitness value is used for the mutation of the next generation. A set of solution that contains good solution for each mutation is kept. Every time when mutation is performed, the offspring is compared against with its parent and all the other solutions in this set for their dominations. The PAES has provided a direct method for controlling the diversity of the pareto optimal, therefore, the premature convergence is less likely to occur and a higher probability to achieve real pareto front.

Deb (1999); Srinivas & Deb (1994); Deb (2001) introduced non-dominated sorting genetic algorithm(NSGA) based on the work of Goldberg & Deb (1991) that can handles any number of objectives. This method ranks individuals based on the non-domination level and the fitness of each individual is determined by the non-domination level of itself. This method can maintain the stability and uniformity of the non-dominated individuals throughout the reproduction. Later, Deb et al. (2002) improved the efficient of this method and achieved a fast and elitist multi-objective evolutionary algorithm based on the non-domination sorting method. This improved version is named as NSGA-II. By applying crowding distance into the sorting method, this improved version shows great advantage in terms of efficiency to either SPEA or PAES.

NSGA-II(Deb et al. 2002) is one of the most effective and efficient multi-objective optimization method that has been widely used in many fields. Although it can handles any number of the objectives, recent research(Ishibuchi et al. 2008) indicates that, when the number of the objectives increases, more individuals have become non-dominated, therefore more evolutionary iteration is needed to achieve convergence. In face, based on the experiments, NSGA-II performs best when the number of the objectives is around three(Ishibuchi et al. 2008). This thesis defines three objectives for the cloth pattern optimization, therefore, NSGA-II outstands itself in the pattern adjusting problem in this thesis.

1.6 Summary

In this chapter, a brief history of the three types of virtual clothing methods in computer graphic has been reviewed.

The geometrical virtual clothing method generates cloth for virtual character by using geometric modelling method, the physical properties of the cloth object is not in its consideration. Therefore, it is used as a modelling tool for generating static cloth geometry and it needs a considerable amount of manual inputs to create a cloth.

The physical virtual clothing method describes the cloth by using a dynamic model. The shape of the cloth is determined by the forces or the energies of each vertex on the cloth mesh. This method not only be able to model the static shapes of the cloth but also be able to simulate its dynamic behaviours of the cloth. The physical virtual clothing method has been widely used in garment industry and animation production. However, because the winkle detail of the simulated cloth is determined by the number of the basic element in the dynamic model used for representing the cloth object. For this reason, the only way to increase the level of detail is to increase the resolution of the mesh or particles. This increases the computational cost.

In the area where the visual appearance is more important that the physical simulation accuracy such as films or games, hybrid virtual clothing method is applied in order to improve the efficiency of the virtual clothing while maintaining high visual realism. The hybrid virtual clothing methods combine different types of modelling or simulation method together in order to compensate the shortcomings of each method to be applied on its own and provides a highly efficiency approach for the application. However, the hybrid method also has its own drawbacks, because it uses some techniques such as data-driven deformation method to simulate the wrinkle instead of producing them by solving the physical equation. The variety of the fine detail wrinkle is often limited by the non-physical deformation method.

The methods reviewed in this chapter are mainly focus at reproducing either the static shape or the dynamic behaviour of the cloth for a particular character. Both the results of cloth modelling and dynamic simulation can not be directly applied to another character with different body shapes or proportions. Large amount of manual operation is often required to create cloth for different characters or transfer a cloth from one character to a different one. Normally, the entire virtual clothing process must be performed from scratch in order to generate cloth for a different character with different body shapes or proportions. This duplication of effort can not be eliminated even when the same cloth design is required to fit to different characters. The current methods tie the character with their cloth together, and they can not be separated. Especially in today's virtual character applications, the number of the different characters that required in the virtual environment has been increased rapidly by the fast development of computer hardware and computer graphic techniques. The low efficiency caused by the duplication of effort in current virtual clothing methods has become a significant obstacle. Therefore, dressing different characters efficiently is still considered as a challenging task.

In order to model cloth from cloth patterns, measurements of the character model is crucial for determining the size of each pattern. This thesis utilises geodesic to mimic the tape measuring process in the tailoring in fashion industry. Moreover, using geodesic also results less variation when the posture of the character changes. However, computing geodesic on the high resolution model by using current geodesic algorithms is a very time consuming process. Moreover, followed with the increasing number of 3D scanned character model, the geometrical representation of the character is no longer limited to polygon, nurbs or subdivision, but also the point cloud. In order to improve the efficiency of the geodesic computation while maintaining high accuracy as well as measuring the point cloud character model, three geodesic algorithms are proposed in this thesis respectively for accurate and approximate geodesic computation on triangulated manifolds as well as approximate geodesic computation on point cloud data set. The most important contribution is that the proposed approximation algorithm can reach linear time complexity with a bounded error on triangulated manifolds. The time consumed for solving the geodesic path between multiple pairs of source and destination has been largely reduced, at the meantime the accuracy of the solution is maintained.

In the real world, in order to produce fit cloth, the size and shape of each cloth pattern are adjusted based on the measurements of the customer. This process requires deep knowledge in tailoring. Current pattern based cloth modelling method models cloth by mimic this process in the computer simulated environment. In practice, adjusting cloth patterns for a particular character still requires many manual operation. Because few animation artists possess such deep knowledge in tailoring, therefore, this method is rarely used in the production of film and games. The automatic cloth pattern adjustment method presented in this thesis considers the process of adjusting cloth patterns as an optimization problem. There are three major objectives in the optimization that need to be considered, the measurements of the character, the integrity of the seam-line on each pattern and the preservation of the shape of each pattern.

For current gradient based optimization methods, preventing algorithm converge into the local minima is always a difficult problem that many researchers are working on. Among these optimization methods, genetic algorithm dwarfs others by its simplicity and efficiency. Moreover, since it is capable of searching through large area of the cost surface, it is less likely to converge into local minima. By using such an approach, the cloth pattern adjusting method presented in this thesis can automatically generates the best combination of the shapes and sizes of each pattern, it will fits the character and the original design of the cloth is preserved. Most importantly, By automating the process of pattern adjustment, the tailoring knowledge that required by current pattern based cloth modelling method is on longer needed. Therefore, animation artists can model varies clothes based on the large amount of existing cloth design patterns in today's fashion industry. Moreover, by automating the process of creating fit cloth for a character, the efficiency of generating cloth for different characters with different body shapes and proportions can be largely improved.

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