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Review of Computer Models for Fabric Simulation
Pregled računalniških modelov za simulacijo tekstilij

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Abstract
3D computer technologies are closely linked to all textile fields ranging from the designing and constructing of fabrics and garments, virtual human body presentations, interactive virtual prototyping to virtual fashion shows and e-trading. This paper offers a review of frequently used methods for fabric simulation. The review is divided into two parts. The first part of the paper comprises currently used techniques, followed by the presentation of basic terms and fabric parameters required for fabric simulations. The second part discusses the approaches and methods for constructing computer models of fabrics. In conclusion, the list of used techniques and parameters for defining a computer fabric model are presented together with given future guidance.
Keywords: CAD/CAM in textiles, fabric simulations, fabric models

Izvleček
Računalniške 3D tehnologije so čedalje bolj prisotne na različnih tekstilnih področjih, od konstruiranja in izdelave tkanin in oblačil, virtualne predstavitve človeškega telesa, interaktivnega virtualnega prototipiranja, do virtualnih modnih revij in e-trgovanja. Prispevek podaja pregled pogosteje uporabljenih računalniških metod za simulacijo tekstilij. Razdeljen je na dva dela: v prvem je opisano trenutno stanje uporabe računalniških modelov za simulacijo tekstilij, temu sledi razlaga osnovnih pojmov in potrebnih parametrov za njihovo simulacijo. V drugem delu so predstavljeni pristopi in metode za njihovo izgradnjo. V zaključkih je podan pregled najznačilnejših uporabljenih tehnik in parametrov, potrebnih za definiranje računalniških modelov tekstilij ter smernice nadaljnjega razvoja.
Ključne besede: CAD/CAM v tekstilstvu, simulacije tekstilij, modeli tekstilij

1 Introduction

Computer-aided technologies are already being used in many areas of the textile industry to improve the efficiencies of the production processes. The main function of computer technology within the textile arena is to help designers when designing new models, textile engineers at the garment development process and retailers of garments at performing their selling activities. Actually computer technology enables all of them to produce more products over shorter duration whilst the development processes are geographically dispersed. In addition, computer technologies enable all participants (engineers, designers, and sellers) to adopt quick responses to market requirements and perform quick fabric and garment design modifications thus allowing their garments to be sold more globally.

Garment simulation has long histories in both computer graphics and textile engineering. Fabric modelling research began within the textile engineering community in the 1930s with the first fabric model developed by Pierce [1]. In the middle of 1980s the computer graphics community started to study fabric

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modelling and animation techniques. These two groups focused on the same problems from different aspects. The textile community's research concentrated on three broad categories: modelling the geometric-mechanical structures occurring at yarn crossings, modelling the mechanics of fabric using continuous elastic sheets and rods, and modelling the macroscopic geometric features of fabric [1, 2]. In contrast the computer graphics community was motivated towards developing simple fabric models with geometric structures that resemble fabric as well as efficiently reproducing the virtual appearance of fabric [1–4]. However, both areas present and study the behaviour of fabrics and garments from their own viewpoints. For example, for several years animators have used models with little consideration of the physical laws derived from the real world. Most of the time animation sequences have shown geometric and rigid objects moving and changing according to simple or complex predefined transformations [1, 5, 6]. During that time the simulation of complex fabric behaviour within real environments can only be reached through an optimal combination of modelling techniques for fabric behaviour and numerical methods. They must together combine the high computation efficiency, stability and visual realism that is required for complex garment forms.

However, during further development by textile and computer engineers, the virtual simulations of fabrics and garments necessitated very complex work because of the combination of used techniques involving physical/mechanical simulation, collision detection, and user interface techniques for creating garments [7]. Nowadays, fabric simulation's potential has been developed for use throughout the garment industry. Over the last decade virtual garments for the garment industry have incorporated more and more computer applications not only regarding graphics but also CAD techniques. Nowadays many usable commercial programs for garment simulation and prototyping are provided by the leading CAD/CAM producer, such as Gerber [8], Lectra [9], Assyst-Bullmer [10], and Optitex [11].

2 Basic terms and definitions

At the beginning this paper presents the basic terms and definitions commonly used when explaining computer simulations of fabrics and garments.

Textile vs. Fabric vs. Cloth: The terms fabric and cloth are used within textile assembly trades (such as tailoring and dressmaking) as synonyms for *textile*. However, there are subtle differences in these terms during specialised usages. *Textile* refers to any material made of interlacing fibres. *Fabric* refers to any material made through weaving, knitting, spreading, or bonding that may be used during the production of further goods (garments, etc.). *Cloth* may be used synonymously with *fabric* but often refers to a finished piece of fabric used for a specific purpose, for example, tablecloth [12]. The term fabric will be used throughout this paper.

Fabric model is a term used for a constructed geometrical, physical and mechanical fabric model for simulating fabric within a computer program; usually within the context of 3D computer graphics [12].

Fabric simulation concerns the modelling of fabric for its realistic behaviour simulation [13]. In other words, fabric simulation is the process of replicating the movement and deformation of a piece of fabric or clothing by mimicking how that fabric would react in the real world.

Garment simulation: means the physical simulation of cloth-like objects for use in 3D computer graphics. Examples of such objects could be virtual clothing with animated 3D character, a tablecloth, flags or curtains etc. [14].

Virtual prototyping of garments: An official definition of virtual prototyping regarding fabrics/garments cannot be found in the literature. In respect of this many definitions for other application areas are presented [15]. The highlights of two of them cover *all product types,* and they can also be used for virtual fabric/garment prototyping.

- Virtual prototyping is a software-based engineering discipline that entails modelling a mechanical system, simulating and visualising its 3D-motion behaviour under real-world operating conditions, and refining/optimising the design through iterative design studies prior to building the first physical prototype [16].
- Virtual prototyping or digital mock-up, is a computer simulation of a physical product that can be presented, analysed, and tested from the concerned product's life-cycle aspects such as design/engineering, manufacturing, service, and recycling as if on a real physical model. The constructing and testing of virtual prototype models is called virtual prototyping [17].

3 Computer simulations of fabrics

The qualities of computer models for fabric simulation depends on several predefined parameters such as fabric properties, available computer models, schemes for performing mechanical simulation, and fabric surface discretisation [3].

3.1 Characterisations of fabrics for computer simulations

Fabrics have by nature special properties that generate interesting shapes when draping or designing 3D shapes of objects. Fabrics can be described as thin, non-homogeneous material in all directions (warp, weft, diagonal) with large deformation under low loading. For successful fabric simulation, the mechanıcal properties are mainly elasticity and viscoelastic parameters, as well as environmental, and need to be defined. In the cases of high dynamic situations viscosity parameters should also be precisely defined [3]. Among elasticity parameters are important Young modulus, shear and bending rigidity modulus, and the Poisson coefficient [1, 18–20].

Initially, researchers focused on input parameters for realistic virtual simulations of real fabrics. They studied a material's behaviour according to its mechanical properties. In the first application of fabric simulations, no measured mechanical and physical properties of fabrics had been used as input parameters. Parameters for different fabric behaviour were set randomly as, for instance, similarly to rubber or they were based on previous experience [3, 21]. As input, researchers also used simplified fabric properties as represented by linear and isotropic behaviour assumptions [22]. Furthermore, some simulation systems were tested for their applicability regarding empirical data such by KES-FB (Kawabata Evaluation System) and FAST (Fabric Assurance Simple Tests [2, 17-19, 23–25]. Moreover, besides the KES-FB parameters fabric drape properties were also used for simulation.

Furthermore, a simulated fabric also reacts with its environment and also the amount of objects reactions, frictions and self-collision detections between fabrics layers have to be taken into account. The most obvious external force exerted on the fabric is universal gravity that should always be taken into account by computer simulation of fabrics. Furthermore, other environmental circumstances should also be included, for instance, if a fabric moves freely in the air or it is in contact with and interacts with the underlying surface i.e. with the human body [3].

3.2 Fabric modelling within the textile community

In fabric simulation, the main research key factor is to understand the materials' properties of fabrics. The textile community's research was concentrated from the beginning on studying the fabric behaviour from the mechanıcal engineering point of view. The research is concentrated on both micro and macro levels when describing the fabric's behaviour [1]:

- micro level: where the fabric's characteristics are defined according to its structure, i.e. interweaving of warp and weft threads in woven fabrics or loops in knitted fabrics,
- macro level: where a fabric is regarded to as a continuum. It is described on the basis of small particles that are interlinked according to laws of physics.

The fabric models are presented as geometrical and continuum models.

a) Geometrical model of fabric

The first fabric model was the geometrıcal yarn-level model developed by Pierce in 1930 [26] and was later modified several times [1]. The model consists of two yam cross-sections constrained by a third yarn segment running perpendicular to the cross-sections. Physical phenomena forming amongst the threads were defined based on laws of physics and mechanics, Figure 1.

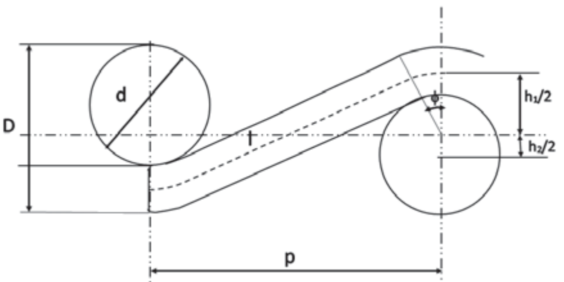

Figure 1: Peirce's geometric fabric model [25]
Legend: l – yarn lenght, h_1 and h_2 – crimp height, ϕ – weave angle, d – yarn diameter, D – sum of the yarn diameters, p – yarn spacing

The results showed that the geometric model was very complex and therefore unsuitable for computer processing at that time.

b) Continuum model of fabric

The observations of fabrics' properties on a continuum level introduced more desirable results. The more commonly used were energy-based and elasticity methods. Energy-based methods attempt to model the parameters and structures of fabric by creating and minimising equations that define the strain energy within the fabric. These methods are classified into two groups as low level structural and high-level continuum models. The low-level methods were used to model a yarn crossing structure and calculated only a few of the conventional mechanical parameters of woven fabric and some of the geometrıcal parameters focused on fabrıcs' cells. The high-level continuum models explored the fabrics' mechanical properties by applying the conventional theory of elastic plates and shells.

De Jong and Postle [27] are known as the investigators and developers of low-level models for fabrics. They developed a model based on yarn deformation, and using that model were able to analyse strain energy independent of yarn structure. They separated the total strain energy of yarn structure into four constituents as bending, torsion, lateral compression and longitudinal tension. With their proposed model, they estimated the load-extension, decrimping and bending rigidity properties for various materials. Their model was modified by Knoll, Hearle and Shanahan [28−30].

The high-level energy-based method for studying fabric properties was first presented by Amirbayat and Hearle [31, 32]. They proposed an energy-based method for modelling the large-scale deformations of a thin, flexible sheet. The reason arose because the conventional elasticity-based techniques for fabric modelling had many limitations. They state that the thin shell theory is only a collection of special-case analyses derived for specific, simple three-dimensional geometries, implying that it is unsuitable for modelling the arbitrary and complex geometries of fabrics. Another energy method was presented by Ly [33] who simulated a three-dimensional buckling of a square fabric piece defined as an anisotropic thin plate under the combined effect of tensile and shear forces. This model's limitation regarding fabric representation is in its specific boundary conditions according to the kinds of fabric.

At the same time, another group of scientists developed fabric models based on the theory of elasticity. Kilby [34] firstly presented the application of an elasticity theory on woven fabrics. He developed planar stress-strain relationships for a simple trellis using conventional elasticity-based analysis. He assumed that fabric can be modelled with a rectilinear trellis in which the elements are pivoted together at their intersection points but do not pass under and over as is characteristic for fabrics. Lloyd, et al. [35] used this method for investigating fabric behaviour folding in respect to its weight. This method was criticised [28] because of the assumption of small strains and deformations. However, in the literature other types of elastic-based methods are reported for fabric modelling. For example Amirbayat [31, 32] modelled a sheet of fabric as a thin isotropic rectangular plate in order to determine the strain necessary to produce buckling when opposing concentrated forces are applied to the sheet. Imaoka et al. [55, 56] developed a continuum mechanics model of fabric based on the large deformation shell theory. Collier, Govendary, Jevšnik [18, 20, 36] presented a finite element approach to modelling the draping behaviour of fabric. They characterised the deformations of fabric whilst draping as a non-linear small-strain/large-displacement. Gan et al. [37] investigated woven fabric deformation as a large displacement, small strain problem and solve it with a nonlinear finite element method. Shell/plate elements are used in woven fabric modelling and when applying them certain points need to be taken into account such as calculations of shell normal, shear elimination, and stress-strain connection determinations [1].

Jevšnik combined the shell-plate theory with the theory of lamina for modelling fused panels. A fused panel was defined as a two layer lamina, Figure 2.

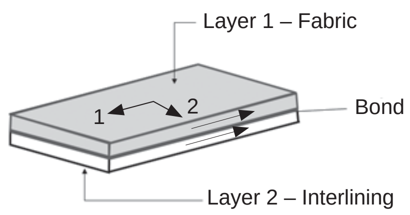

Figure 2: Fused penal of fabric and fusible interlining two layer lamina [19]

Each layers (fabric and interlining) were described with its properties i.e.: specific density, fabric thickness and rheological parameters such as Young's and shear modulus in warp and weft directions, and the Poisson ratio. The connection between the fabric and fusible interlining was considered as ideal with negligible thickness of thermoplastic. For both fabric and fusible interlinings it was considered that they were a continuum with homogeneous and orthotropic properties [18, 36].

3.3 Fabric modelling within the computer graphic community

Further development was taking place at the same time within the textile engineering and computer arenas. In garment simulation the main key research factor is to develop a suitable fabric model for studying mechanical and physical legality. In contrast to the textile engineers the computer engineers try to develop fabric models with low computation costs and higher efficiency [1]. Fabric modelling techniques within the computer graphic community are classified into three categories: geometrical, physical, and hybrid.

a) Geometrical-based models

Geometrical models were the first techniques to be used in computer graphics for fabric simulation. The models were simple geometrical formulations of fabric without the fabrics' physics of dynamic and mechanical properties such as wrinkle formulations on local surfaces. These models were unsuitable for complex reproducible fabric simulation. They focused on appearance, particularly folds and creases, which were represented by geometrical equations. The geometrical models' characteristics were of high controllability and predictable animation sequences. However, these models were also insufficient for responding to situations for exhibiting high variability. Weil presented the first attempt at fabric simulation using a geometrical model in 1986 [38]. At the same time, method was also developed for rendering a fabric's surface once it is in free-hanging shape. The surface fabric was described using constraint points by tracing catenaries between each pair. A line between constraint points refers to the *(row, column)* coordinates through which a line scan-converted from one point to the other would pass within the grid coordinate system. For example, if one constraint point was at grid coordinate (2,3) and another was at (5,3), the line between the two points would include grid coordinates (3,3) and (4,3), Figure 3.

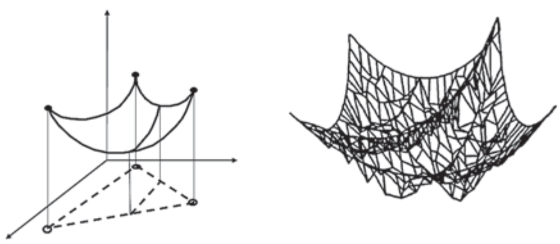

Figure 3: Weil`s geometrical model (a) and simulated fabric (b) [37, 38]

A geometrical method for simulating the wrinkles of fabric by rectangular hanging between two points under additional mechanical constraints such as stretching, bending and gravitational forces was developed by Tailler et al. [40]. The first attempt at automation of garment manufacturing using the geometrical model for simulating a garment's parts was done by Hints et al. [41]. They constructed the first garment shape adapted to the body by interpolating a user-defined set of points. Agui et al. presented the next attempt at computer modelling the sleeve on a bent arm [39]. They constructed the fabric as a hollow cylinder consisting of a series of circular rings. The configurations of the folds on the sleeve were constructed as a consequence of the differences in curvatures between the inner and outer parts of the bent sleeve. The researchers Ng et al. [33] used a geometrical approach for developing an animation tool for the quick reproductions of fabric images. They presented the fabric as two layers that consisted of a series of sections with identical numbers of vertices on each layer, Figure 4.

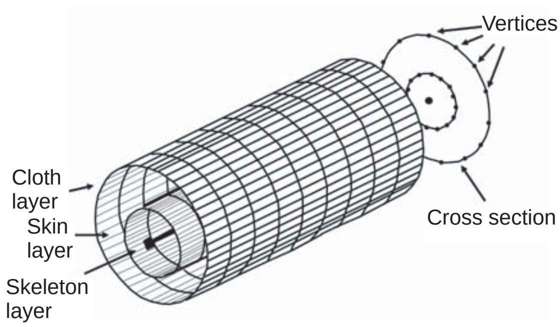

Figure 4: Structure of cloth (fabric), skin and skeleton [33]

When using the model the folds occurred as a result of the underlying structural formations. Moreover, a set of rules was developed for generating folds automatically. A fully geometrical approach for non-extensible fabric deformation was developed and simulated by Ming Chen and Kai Tang [22]. That model was purely geometrical and did not involve stiffness coefficients or elastic modulus regarding problem formulation. It was able to simulate for example the wrinkles, only theoretically. The obtained simulation for a skirt in Figure 5 was achieved for 100% non-extensible fabric [22]. The mentioned method has many conservative solutions; therefore their simulations are very artificial.

Figure 5: Skirt model deformation: the initial shape and the deformation shapes because of different postures [22]

All the mentioned models haven't included any mechanical properties but by definition the points and their interpolations simulated the imitations of real fabric behaviour. The folds' deformations were generated along the lines of a fabric's surface, and the folds could be either automatically determined or manually edited [22]. The main interest of the used geometrical models for fabric simulation application is to have a computationally efficient and highly controllable model which can perform the simulation well within certain predefined fabric behaviour. Geometrical models do not consider the physical properties of fabric. Rather they focus on appearance, particularly folds and creases, which they represent by geometrical equations. Geometrical techniques require a considerable degree of user intervention; they can be regarded as a form of advanced drawing tool.

b) Physical-based models

Physically-based models represent the fabric as continuously divided on triangular or rectangular grids. The points have defined finite masses at the intersections. The numbers of points are defined according to the used problems and techniques. The continuum models for computer simulation can find solutions as fabric models based on simple geometry and also for more complex formulations of fabric structure presentation such as models based on energy and elasticity. The main continuum mechanical models provide accurate fabric behaviour simulation derived at directly from mechanical laws. In contrast to the geometrical model, the continuum models need to be highly adaptable for accurate computations of the dynamics of objects having well-defined mechanical constraints and relatively stable mechanical contexts. The continuous models are independent of geometrical representation therefore with them it is possible to solve complex numerical problems by integrating various constraints. The complex computation requirements are the reason for their slow performances. The Lagrange or finite methods are used for fabric behaviour calculations.

The more common models for interpreting the interactions amongst defined points are energy-based models, models based on the theory of elasticity, particle-based and finite element models.

c) Energy-based models and models based on the theory of elasticity

Energy-based models and models based on the theory of elasticity are the more common models for interpreting the interactions amongst defined points. The finite element method and Lagrange equations are mainly used for the problem solving of fabric behaviour. Next, very often used techniques for modelling are article-based models sometimes referred to as mass-spring models. During this modelling technique an object is assumed to be a collection of mass points that are interconnected by structural, bend and shear springs through a grid structure. The mass points (particles)

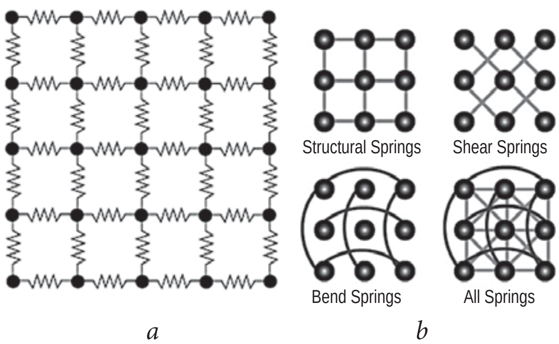

Figure 6: Particle-based model: the simple part of the particle model for fabric simulation (a) and the three types of mass springs (b) [1]

are interconnected by linear springs within the position and velocity at a certain time and mass [1–3]. The way the springs are connecting the particles (the topology of the object) and the differences in strength of each spring influence the behaviour of the object as a whole. A simple particle model for fabric simulation [1-3] is shown in Figure 6.
The first major system for simulating fabric and deformable surfaces was developed by Terzopoulos et al [21]. His model was used based on the elasticity theory and the Lagrange formulation for the calculation of fabric behaviour, Figure 7.

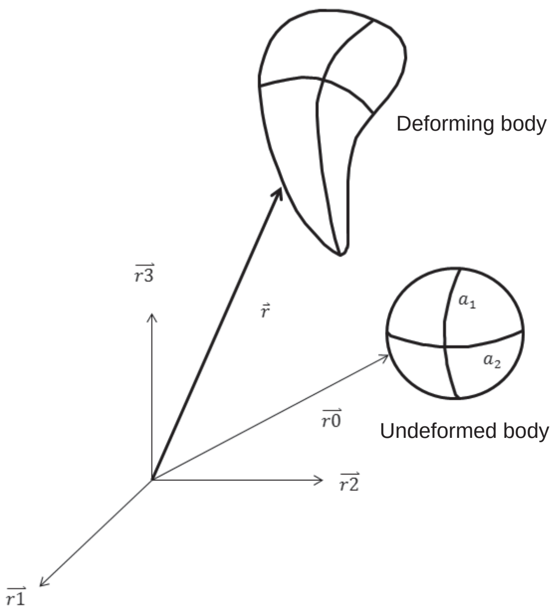

Figure 7: Terzopoulos model for deformable subjects [21]

A physical-based model for modelling draped fabric in 3D environmental by a 2D grid was developed by Feynman [42]. He proposed an energy equation from the theory of elastic plates when energy is at a minimum when the fabric is draped:

$$E(P_{ij}) = k_s E_{elast\ ij} + k_b E_{bend\ ij} + k_g E_{grav\ ij} \quad (1)$$

where P_{ij} is energy at point, k_s, k_b, k_g are elasticity, bending, density constants, $E_{elast\ ij}$ is elasticity energy, $E_{bend\ ij}$ is bending energy and $E_{grav\ ij}$ is gravitational energy.

Terzopoulos's model was later extended by Thalaman et. al [3, 43]. Thalaman's research team has dealt with the visualisation problems using an analogous approach for the production of a garment by manufacturing. This principle of garment prototyping is still a priority during the computer-based garment simulation of fabrics. Her work was mainly focused on collision detection and response, and the designing a complete set of clothing. Her research colleague Volino et al. [44, 45] used the theory of elasticity and Newtonian dynamics to simulate fabric, and improved the collision detection of Thalaman`s system. Breen et al.[1] simulated fabric behaviour using the particle-based model. This method treats the crossing points of the warp and weft threads as particles. The Breen et al. simulation was in two stages. In the first, particles are allowed to fall freely (Figure 8a). In the second stage (Figure 8b), an energy minimisation process is applied to the inter-particle energy functions to generate fine detail in the shape of the fabric.

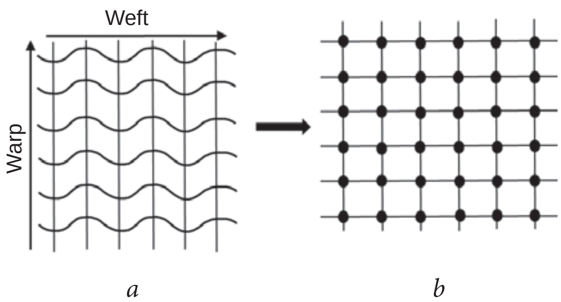

Figure 8: Particle representation (b) of plain weave (a) fabric [1]

Zhang and Yuen [46] presented a fast fabric simulation method using multilevel meshes based on the Provot model [47]. The aim of this method was to speed up fabric simulation whilst achieving realistic simulation results**.** At each phase, the mesh triangular size is smaller than that of the previous phase and therefore calculation is faster. The multilevel method provided very good results especially for fabric draping simulation, Figure 9 [46].

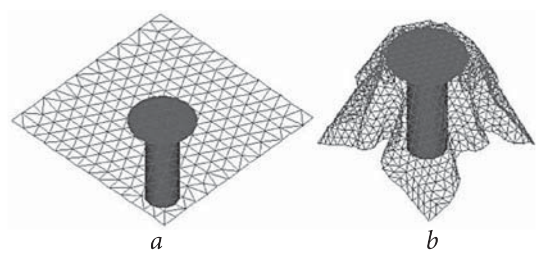

Figure 9: Draping simulation of a piece of fabric hanging over a disc plate with multilevel meshes: initial position (a), final position after simulation phase (b) [46]

d) Particle-based approach

This particle-based approach to fabric modelling was first applied to the problem of computing static drape [2]. A piece of fabric is modelled as a two-dimensional array of particles conceptually representing the crossing points of warp and weft yarns within a plain weave. The various inter-crossing strain energies are represented by energy functions parameterised by simple geometrical relationships amongst particles. These energy functions take into account the four basic mechanical interactions of yarn collision, yarn stretching, out-of-plane bending and trellising (in-plane bending) that are shown graphically in Figure 10. The model does not consider twisting strain, however. The strain energy for crossing particle *i* is given by equation [2]:

$$E_i = E_{repel\ i} + E_{stretch\ i} + E_{bend\ i} + E_{trellis\ i} \quad (2)$$

where E_i is strain energy for crossing article, $E_{repel\ i}$ is artificial energy of repulsion that effectively keeps, is $E_{stretch\ i}$ energies of tensile strain between each particle and its four-connected neighbours, is $E_{bend\ i}$ energy due to yarns bending out of the local plane of the fabric and $E_{trellis\ i}$ is energy due to bending around a yarn crossing in the plane.

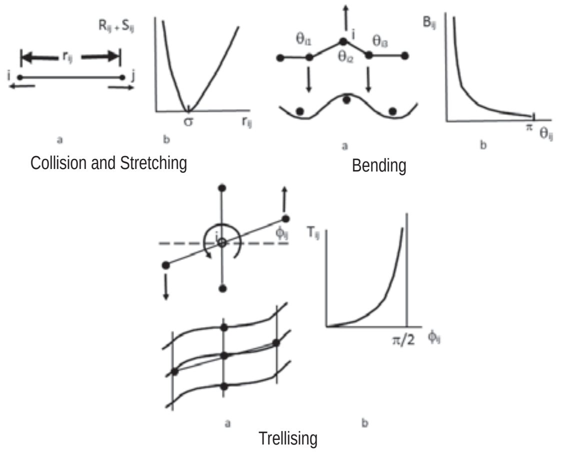

Figure 10: Fabric model's energy function [2]

Breen [1] simulated the static drape of fabrics and later Eberhardt et al. [48] simulated the fabric drape as dynamic phenomena on the table, on the sphere, and the castle, and the final drape was quick and quite realistic. Particle-based models were used for many applications. Ocabe et al. [49] used visualisation tools focused on automisation of the traditional garment manufacturing processes. Li et a1. [50] simulated fabric immersed within an airflow, Gröller et al. [51] modelled the microstructure of the knitted fabrics. They also built a rendering method for the simulation of knitted fabrics (fabric modelling and animation). The classic mass-spring model shown in Figure 11 was used by Provot [47].

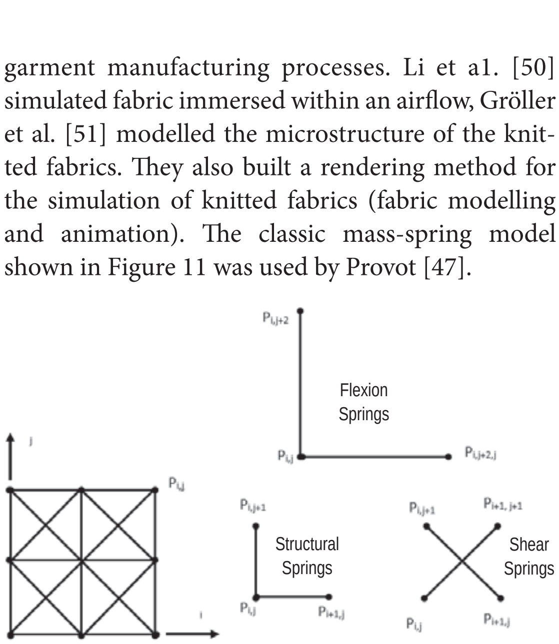

Figure 11: Classical mass-spring model [47]

Furthermore, Baraff and Witkin [52] used a triangulated mesh to represent the fabric structure, using a continuum formulation on a per-triangle basis for in-plane deformation, and the angle between adjacent triangles to measure out-of-plane deformation, Figure 12.

Figure 12: Baraff's and Witkin's simulation using continuum mechanics [52]

e) Finite element method

The finite element is a frequently used method for numerical analysis and is based on the usage of matrix algebra. Solving problems was based on discretisation of arbitrary construction into suitable finite elements. This method is also being developed today as a special scientific discipline within the textile area.

The development of programs for solving nonlinearity problems is producing very satisfactory results as in the cases when large displacements and small deformations appear that are significant for a fabric.

R. Collier et al. were the first to use the finite element method for modelling fabric drape [18]. The fabric was described as two-dimensional and orthotropic materials with linear properties. He used Young's and shear modules for calculating within warp and weft directions, measured on KES FB system and Poisson's ratio to sum up as per literature. The calculated drape coefficient was analysed by experimental measurement using a Cusik drape metre. Drapability over the square table was analysed by Govindaray using the finite element method [20]. He studied the draping behaviour of fabrics by using a non-linear finite element method based on a classical non-linear plate theory. J. Hu et al. [53] used a geometrically nonlinear finite-volume method for the numerical simulation and analysis of fabric drape. An initially flat circular fabric sheet is first subdivided into a number of structured finite volumes by mesh lines along warp and weft directions, resulting in rectangular internal volumes and triangular or quadrilateral boundary volumes. Deformation and rotation as a small strain characteristic of using numerical calculations fabric was investigated by Yu [54]. He modelled the fabric using plate and shell elements and the "Alpha" – constant stiffness matrix iterative method was used to reduce simulation time. The advantage of this method is that less computation time is required but the disadvantage is that the degree of non-linearity in the drape problem is incompletely represented by the unknown coefficient matrix during iteration.

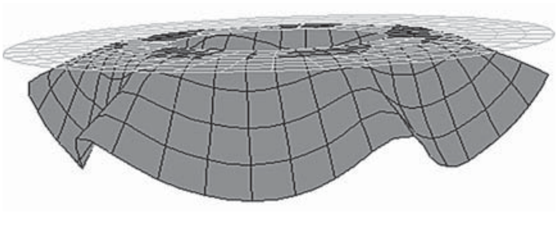

Figure 13: Drape simulations of fused paned using finite elements [36]

S. Jevšnik [36] used the finite elements method for modelling and simulating fused panel drape, Figure 13. The fused panel was treated as a two layer laminate; one lamina was fabric and the other lamina was the fusible interlining, therefore *the mechanical model of a fused panel was based on the laminate theory.* The author also simulated the extension and shear properties according to a measuring process using KES methodology for fabric and fusible interning [19, 36].

3.4 Hybrid model

The hybrid techniques combine the physical and geometrical methods. The advantages of combining the physical and geometrical methods were first recognised by Rudomin, Kunii, Taillefer and Tsopelas. Rudomin [55] developed a model that is a combined geometrical-physical model. He developed a method for roughly estimating fabric suspended with a restraint points set. During the same period Kunii [56] developed a hybrid particle model for the simulation of the wrinkles on bent arms. The particle system is made up of a grid where each node is linked to its neighbours by springs. Similar wrinkles were modelled by Tsopelas [57]. He treated garments as thin cylindrical tubes under axial loads and simulated garment folds using the deformation theory. This process focuses on regions where folds are most likely to appear, that is those regions with large curvatures. These occur at the back of the knees. Taillefer [40] categorised the folds of a hanging fabric into two types, horizontal and vertical, as shown in Figure 14.

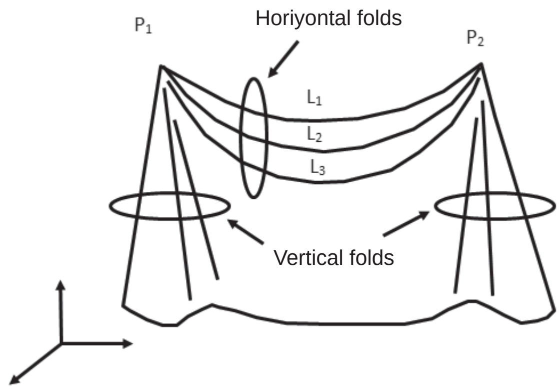

Figure 14: Simulation of horizontal and vertical types of folds [40]

The bending properties are one of the most influential parameter for realistic fabric simulation especially for presentation involving wrinkling and folding. Pabst et. al. [58] presented bending fabric model that makes use of measured moment-curvature data and a seam model that significantly improves the realism of garment simulations. The efficient physically-based bending model using hysteresis in fabric simulation was developed also by Wong et al [59]. They compared the bending model with previous methods and plasticity models [1, 17, 44]. The model is not much more complicated than previous models, and experiments showed that with a small extra computation time satisfactory bending hysteresis and plasticity could be obtained [58]. One of the last developed methods for physically-based fabric simulation is Continuum-based Strain Limiting (CSL) method which is suitable for anisotropic biphasic materials [61].

4 Accuracy of fabric computer simulations

The accuracy of computer processing fabric simulation is, besides the selected model, the next important parameter. However, the accuracy of computer simulation depends on the selected model of a fabric according to the phenomenon of its deformation. In the case of 2D textile products (flags, curtain) the simplest mathematical models are chosen for calculation (linear mathematical models). For garments and other 3D textile forms, more complex models have to be selected such as polynomial models, interval models, and discrete models. The discrete model is seldom interesting for fabric simulation models [3], Figure 15.

Continuum mechanics studies the states of fabrics' surfaces and volumes through quantities varying continuously within space and time. Each physical parameter of the material is represented by a scalar or vector value continuously varying according to position and time. Mechanical laws can then be represented as a set of partial differential equations which hold throughout the volume of the material.

Particle systems discretise the material itself as a set of point masses ("particles") that interact with a set of "forces" that approximately model the behaviour of the material [3]. Computational time for fabric simulation depends on the fabric object's discretisation. The density of discretisation depends on the method of numerical simulation, the shapes and motions of the fabrics, as well as the available computer hardware. Triangular meshes are the more common representations for complex fabric objects [3].

The mechanical computer models of fabrics have to provide the simulation of fabric properties rapidly and realistically. The performance of fabric simulation depends on adequate implementation of algorithms and numerical methods. In the literature, there are many ways of compiling computer systems for fabric simulation and their performances are improving from year to year [1, 3].

Ultimately, the rendering process of the fabric should also be included for the desired end-look of

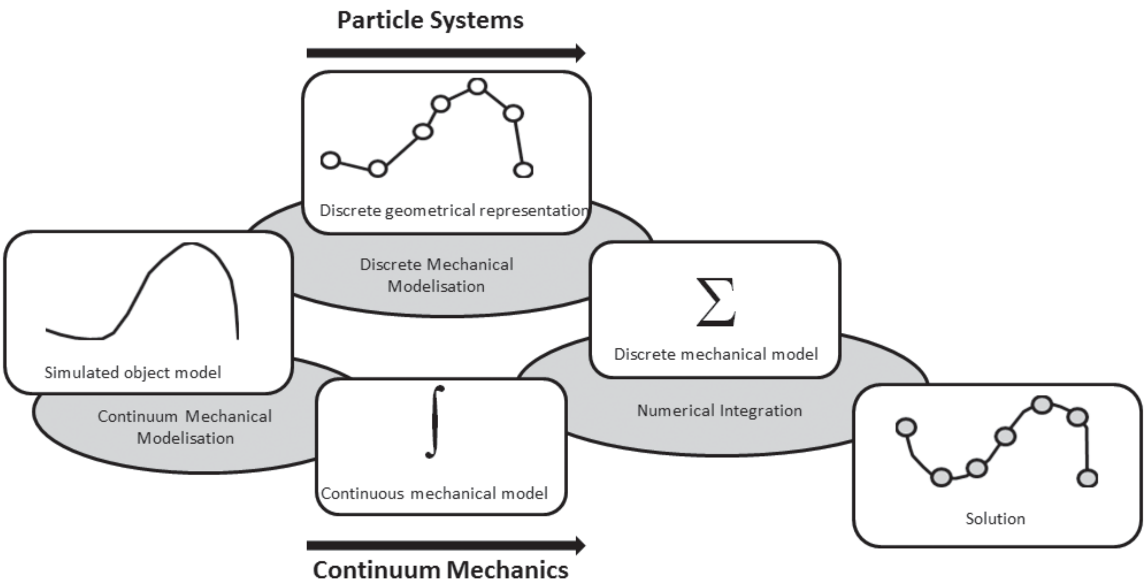

Figure 15: A particle system and continuum mechanics [3]

the simulated fabric. Volino and Magnenat-Thalmann in their book pointed out four parameters having a significant influence on the success of fabric simulation [3]:

- *scope:* the simulation system should support the mechanical behaviour and the properties to be simulated.
- *accuracy:* the mechanical system should be simulated in a very accurate way within whatever possible context.
- *robustness:* the simulation system should be able to compute the mechanical system whatever the context, which can vary along the simulation regarding accuracy, and no particular situation should cause the simulation to fail.
- *speed:* speed is obviously one of the major values of a good mechanical simulation system. The speed is validated by offline computation systems, interactive applications, and real-time applications.

5 Comparisons between used methods

Table 1 collates and presents some of the used models and techniques for fabric simulation. The collected data based on literature reference [39] and authors' literature studies and own research experiences. Certain of better known models are also described in the previous paragraphs.

The geometrical techniques for constructing the computer models of fabrics have not include the measured fabric parameters, because they were constructed on the same assumptions of fabric parameters. The advantage of this is that the computation time is faster than by other modelling techniques. Physical techniques are the most commonly used for modelling fabric models because of reasonable computation time and quite good realistic presentations of virtual fabric behaviour. The simulation of fabrics' behaviour using the hybrid models provides very good realistic presentations of fabrics within a virtual environment but the computation time is very time-consuming.

6 Conclusions

Visualisation of a garment within a virtual environment is an exciting branch for textiles as well as for computer graphics engineers. The correct selection of a fabric model for virtual simulation is a very important issue during the designing of an efficient fabric simulation system. Nowadays developed fabric models for obtaining realistic fabric behaviour are still insufficient even though many already complex applications have been presented for virtual clothing simulation. From the presented review it can be concluded that over the past decades within the textile engineering and computer arenas new significant solutions of models for fabric simulations have not been forthcoming. The development of fabric models for computer simulation was mostly focused on physically-based models or their hybrids. Their main advantage is good realistic presentations of simulated fabrics. The geometrical techniques are based on the appearance of the fabric sample without the mechanical and physical properties of fabric. Researchers have presented more or less upgraded or modifications of existing methods. The reasons are probably in the necessity of developing highly efficient computer performances that can simulate fabric on the micro level with the least possible limitations regarding fabric characteristics.

Table 1: Comparison of used techniques and parameters for defining fabric models regarding simulations

Models	Authors	Used techniques	Parameters for defining the model
Geometrical models	Weil [38]	Curve fitting, subdivision, relaxation	Position of constraint points
	Agui et al. [39]	Polygonization, relaxation,	Bending angle, thresholds
	Hinds et al. [41]	3D interaction, interpolation	Geometrically offset from the object
	Ng et al. [39]	Mapping	Various functions
	Ming Chen and Kai Tang [22]	Algorithm for interpolation	Thresholds, Position of constraint points

Models	Authors	Used techniques	Parameters for defining the model
Physical models	Feynman [42]	Energy minimization, Multigrid method	Elasticity, bending, gravity
	Terzopoulos et al. [21]	Elasticity theory, Lagrange`s theory	Density, damping curvature tensor,
	Aono [39]	Elasticity theory, D`Alemberts`s principle, finite difference	Stress, strain, Young's rigidity, Poisson`s ratio, density, damping, constantly lame
	Sakaguchi et. al. [39]	Newtonian dynamics, the deformable model	Density, elasticity, viscosity, plasticity
	Thalmann et al. [43]	Deformable model, Newtonian dynamics	Deformable model`s parameters
	Volino et al. [44]	Newtonian dynamics, elasticity theory	Stress, strain, Young's modulus, rigidity, Poisson's f »efficient, density, thickness
	Breen et al. [1]	Energy minimization, Newtonian dynamics	Repulsion, stretching, bending, trellis, gravity
	Ocabe et al. [49]	Energy minimization, elasticity theory	Elongation, shearing, bending, twisting, density
	Li et al. [50]	Simplified Navier-Stokes equation, Bernoulli's equation, deformable model	Air velocity, deformable model's parameters
	Provot et al. [47]	Newtonian dynamics, Euler integration	Mass, stiffness, damping, viscosity
	Ng et al. [39]	Energy minimization, multigrid method	Elasticity, bending, gravity
	Jevšnik [36]	Newton-Raphsonova method, shell/plate theory Laminate theory	Shear, bending modulus, Young`s and Poisson' modulus, mass
	Zhang et. al. [46]	Newtonian dynamics, Euler integration, Multi mesh	Bending force, mass, constraint points
	Wong et. al. [59]	Triangle mesh Bending hysteresis	Forces for bending and unbending, Bending hysteresis loop, Residual curvature
	Pabst et. al [58]	Bending element consisting of two adjacent triangles	Bending stiffness
Hybrid models	Rudomin [55]	Convex hull, the deformable model	Shape of the object, deformable model's parameters
	Kunii et al. [56]	Energy minimization, singularity Theory, curve fitting	Mass, stiffness, positions of characteristic points
	Tailleler [39]	Curve fitting, relaxation	Positions of hanging points, stretching, bending, weight, self-repulsion
	Tsopelas [57]	Thin-wall deformation, elastic, NURBS fitting	Thickness, diameter, rigidity
	Dhande et.al. [39]	Swept surface generation	Directrix curve, generatrix curve

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References

1. HOUSE, H. Donald, BREEN, E. David. *Cloth Modeling and Animation*. Massachusetts : A. K. Peters Natick, Ltd. Natick, 2000, 344.
2. HU, Jinlian. *Computer technology for textiles and apparel*. Cambridge : Woodhead Publishing Series in Textiles: Number 121, 2011, 392.
3. VOLINO, Pascal, MAGNENAT –THALMANN, Nadia. *Virtual clothing, Theory and practise*. Berlin : Springer-Verlag, 2000, 283.
4. JEVŠNIK, Simona, KALAOĞLU, Fatma, ERYURUK, Selin Hanife, BIZJAK, Matejka, STJEPANOVIČ, Zoran. Evaluation of garment fit model using AHP. *Fibres & Textiles in Eastern Europe,* 2015, 23, 2(110) in print.
5. STJEPANOVİČ, Zoran. IMB 2006 – Novelties in the Field of the 3D Virtual Prototyping. *Tekstilec*, 2006, **49**(7/9), 117–121.
6. JEVŠNIK, Simona, STJEPANOVIČ, Zoran, CELCAR, Damjana. Virtual clothes´ simulations. In *1st International Conference I Love Inter/National Fashion* : *book of proceedings*. Ljubljana, April 2–4, 2009, 67–74.
7. VOLINO, Pascal, CORDIER, Frederic, MAGNENAT-THALMANN, Nadia. From early virtual garment simulation to interactive fashion design. *Computer-Aided Design, 2005,* **37**, 593–608, doi: 10.1016/j.cad.2004.09.003.
8. Gerbertechnology [online] [accessed 7.3.2014]. Available on World Wide Web: http://www.gerbertechnology.com.
9. Lectra [online] [accessed 7.3.2014]. Available on World Wide Web: http://www.lectra.com.
10. Assystbullmer [online] [accessed 7.3.2014]. Available on World Wide Web: http://assystbullmer.co.uk/.
11. OptiTex [online] [accessed 7.3.2014]. Available on World Wide Web: http://www.optitex.com.
12. Cloth modeling [online]. *Textile terms and definitions [*accessed 7.3.2014]. Available on World Wide Web: http://www.ttandd.org/.
13. Textile [online]. *Wikipedia : the free encyclopedia* [accessed 7.3.2014]. Available on World Wide Web: http://en.wikipedia.org/wiki/Textile.
14. CHITTARO, Luca, CORVAGLIA, Demis. 3D Cloth and Garment Simulation based on Web Technologies, *Convegno Tecnico Scientifico*, Torino, November 2003.
15. The availability and capabilities of 'Low-End' virtual modelling (Prototyping) Products to enable designers and engineers to prove concept early in the design [online] [accessed 7.3.2014]. Available on World Wide Web: http://www.lboro.ac.uk/microsites/mechman/research/ipm-ktn/pdf/Technology_review/virtual-prototyping-early-in-the-design-cycle.pdf.
16. WANG, Gary. Definition and Review of Virtual Prototyping, *Journal of Computing and Information Science in Engineering*, 2003, **2**(3), 232–236, doi: 10.1115/1.1526508.
17. HOUSE, H. Donald, BREEN, E. David, GETTO, H. Phillip. A Physically Based Particle Method of Woven Cloth. *The Visual Computer,* 1992, **8**(5–6), 264–277, doi: 10.1007/BF01897114.
18. COLLİER, Joan R., COLLIER, Billie J. Drape Prediction by Means of Finite Element Analysis. *Journal of Textile Institute*, 1991, **82**(1), 96–107, doi: 10.1080/00405009108658741.
19. JEVŠNIK, Simona. Predicting mechanical properties of fused panel. *Fibres & textiles in Eastern Europe*, 2000, **8**(4), 54–56.
20. CHEN, B., GOVİNDARAY, Muthu. A parametric Study of fabric drape. *Textile research journal*, 1996, **66**(1), 17–24, doi: 10.1177/004051759606600103.
21. TERZOPOULOS, Demetri, PLATT, *John* C., BARR, Alan H., FLEISCHER, Kurt. Elastically deformable models. In *ACM Computer Graphics, SIGGRAPH'87 : book of proceedings*. Anaheim, California, 1987, **21**, 205–214.
22. CHEN, Ming, TANG, Kai. A fully geometric approach for developable cloth deformation simulation. *Visual Computer*, 2010, **26**, 853–863, doi: 10.1007/s00371-010-0467-5.
23. CHEN, Bijian, GOVİNDARAY, Muthu. A Physically Based Model of Fabric Drape Using Flexible Shell Theory. *Textile research journal*, 1995, **65**(6), 324–330, doi: 10.1177/004051759506500603.
24. DE BOSS, A. *The FAST System for Objective Measurement of Fabric Properties, Operation, Interpretation and Application. CSIRO Division of Wool Technology, Sydney, 1991.*

25. KAWABATA, Sueo. *The Standardization and Analysis of Hand Evaluation*. Osaka : Textile Machinery Society of Japan, 1980, 97.
26. PEIRCE, F. T. The Handle of Cloth as Measurable Quantity. *The Journal of the Textile Institute*, 1930, **21**(9), 377–416, doi: 10.1080/19447023008661529.
27. DE JONG, S., POSTLE, R.: An Energy analysis of woven-fabric mechanics by mena of Optimal-control theory. Part I: Tensile properties. *Journal of the Textile Institute*, 1977, **68**(11), 350–361, doi: 10.1080/00405007708631412.
28. HEARLE, J. W. S., SHANAHAN W. J. An Energy Method for Calculations in Fabric Mechanics, Part I: Principles of the Method. *Journal of the Textile Institute,* 1978, **69**(4), 81–91, doi: 10.1080/00405007808631425.
29. KNOLL, A. L. The Geometry and Mechanics of the Plain-Weave Structure: A Comparison of the General Energy Method of Analysis and Previous Models. *Journal of the Textile Institute,* 1979, 70(5), 163–171.
30. SHANAHAN, W. J. HEARLE, J. W. S. An Energy Method for Calculations in Fabric Mechanics, Part II: Examples of Application of the Method to Woven Fabrics. *Journal of the Textile Institute,* 1978, **69**(4), 81–91, doi: 10.1080/00405007808631426.
31. AMİRBAYAT, J., HEARLE, J. W. S. The Complex Buckling of Flexible Sheet Materials—Part II. Experimental Study of Three-Fold Buckling. *International Journal of Mechanical Science,* 1986, **28**(6), 359–370, doi: 10.1016/0020-7403-(86)90055-X.
32. AMİRBAYAT, J., HEARLE, J.W.S. The Anatomy of Buckling of Textile Fabrics: Drape and Conformability. *Journal of the Textile Institute,* 1989, **80**(1), 51–69, doi: 10.1080/00405008908659185.
33. LY, Nhan G. A Model for Fabric Buckling in Shear. *Textile Research Journal,* 1985, **55**, 744–749.
34. KİLBY, W. F. Planar Stress-Strain Relationships in Woven Fabrics. *Journal of the Textile Institute,* 1963, **54** (1), 9–27, doi: 10.1080/19447026308659910.
35. LLOYD, D. W., SHANAHAN, W. J., KONOPASEK, M. The Folding of Heavy Fabric Sheets. *International Journal of Mechanical Science,* 1978, **20**(8), 521–527.
36. JEVŠNIK, Simona. *The Analysis of Drapability of Shell Fabric, Interlining and Fused Panel as Assembly Parts of a Garment : Doctoral Dissertation. Maribor, University of Maribor, 2002.*
37. GAN, L., LY N. G. STEVENS, G. P. A Study of fabric deformations using nonlinear finite elements. *Textile research journal,* 1995, **65**(11), 660–668, doi: 10.1177/004051759506501106.
38. WEIL, Jerry. The synthesis of cloth objects. In *ACM Computer Graphics, the 13th annual conference on computer graphics and interactive techniques : book of proceedings.* 1986, 49–53, doi: 10.1145/15922.15891.
39. HİNG, N. Ng, GRİMSDALE, L. Richard. Computer Graphics Techniques for Modeling Cloth. *Journal IEEE Computer Graphics and Application*, **16**(5), 1996, 28–41, doi: 10.1109/38.536273.
40. TAİLLEFER, F. Mixed Modeling. In *Compugraphics, 1st International conference on computational graphics and visualization techniques : book of proceedings*. Sesimbra, Portugal, 1991, 467–478.
41. HINDS, B. K., McCARTNEY, J. Interactive garment design. *The Visual Computer*, Springer-Verlag, 1990, **6**(2), 53–61, doi: 10.1007/BF01901066.
42. FEYMANN, Karl Richard. *Modelling the appearance of cloth : Master thesis*. Massachusetts Institute of Technology, 1986.
43. MAGNENAT-THALMANN, Nadia, CORDIER, F., VOLINO, Pascal, KECKEISEN, Michael, KIMMERLE, Stefan, KLEIN, Reinhardt, MESETH, Jan. Simulation of Clothes for Real-time Applications. In *"Interacting with Virtual Worlds", 25th Annual Conference of the European Association for Computer Graphics : book of proceedings.* Grenoble, 2004.
44. VOLINO, Pascal, MAGNENAT-THALMANN, Nadia. Developing simulation techniques for an interactive clothing system. *Virtual Systems and Multimedia : book of proceedings.* Geneva, Switzerland, 1997, 109–118.
45. VOLINO, Pascal, CORDIER, Frederic, MAGNENAT-THALMANN, Nadia. From early virtual garment simulation to interactive fashion design. *Computer-Aided Design,* 2005, **37**, 593–608, doi: 10.1016/j.cad.2004.09.003.
46. ZHANG, Dongliang, YUEN, M. F. Matthew. Cloth simulation using multilevel meshes. *Computers & Graphics,* 2001, **25**, 383–389, doi: 10.1016/S0097-8493(01)00062-0.

47. PROVOT, Xavier. Deformation constraints in a mass-spring model to describe rigid cloth behavior. *Graphics Interface***,** 1995, 147–154.
48. EBERHARDT, Bernhard, WEBER, Andreas, STRASSER, Wolfgang. A Fast, Flexible, Particle-System Model for Cloth Draping. *IEEE Computer Graphics and Applications,* 1996, **16**(5), 52–59, doi: 10.1109/38.536275.
49. *OKABE,* Hidehiko, IMAOKA, Haruki, TOMİHA, Takako, NİWAYA, Haruo. Three-dimensional apparel CAD system. ***In*** *Computer Graphic, SIGGRAPH*'92 *: book of proceedings. Chicago, 1992, 105–110.*
50. *LI, Ling, DAMODARAN, Murali, GAY, K. L. Robert. A Quasi-Steady Force Model for Animating Cloth Motion. In IFIP International Conference on Computer Graphics : book of proceedings.* North-Holland, Amsterdam, 1993, 357–363.
51. GRÖLLER, Eduard, RAU, T. Rene, STRAßER, Wolfgang. Modeling textiles as three dimensional textures. In *Eurographics Rendering Workshop 1996 : book of proceedings.* Porto, Portugal : Springer-Verlag Vienna, June 1996, 205–214, doi: 10.1007/978-3-7091-7484-5_21.
52. BARAFF, David, WITKIN, Andrew. Large steps in cloth simulation. In *SIGGRAPH 98, Computer Graphics Proceedings, Annual Conference Series ACM, ACM Press/ACM SIGGRAPH : book of proceedings.* Orlando, 1998, 43–54.
53. HU, J., CHEN, S., TENG, J. G. Numerical Drape Behaviour of Circular Fabric Sheets Over Circular Pedestal. *Textile Research Journal*, 2000, **70**(7), 593–603.
54. YU, D. K. C., KENNON, R. POTLURİ, P. Computer-Based 3D Modelling of the Drape of Woven Fabric. *Strojniški vestnik*, 1999, 677–684.
55. RUDOMIN, J. Isaac. *Simulating cloth using a mixed geometry-physical method* : *PhD Thesis*. US, Department of Computer Science, University of Pennsylvania, 1990.
56. KUNII, T. L., GOTODA, H. Modeling and animation of garment wrinkle formation processes. *Computer Animation'90 : book of proceedings*. New York : Springer-Verlag, 1990131–146.
57. TSOPELAS, Nikitas. Animating the crumpling behavior of garments. In *2nd Eurographics Workshop on Animation and Simulation* : *book of proceedings*, 1991, 11–24.
58. PABST, Simon, KRZYWINSKI, Sybille, SCHENK, Andrea, THOMASZEWSKI, Bernhard. Seams and bending in cloth simulation. In *Workshop in virtual reality interactions and physical simulation, VRIPHYS.* Grenoble, France, 2008, 31–38.
59. WONG, T. H., LEACH, G. ZAMBETTA, F. Modelling bending behaviour in cloth simulation using hysteresis. *Computer graphics forum,* 2013, **32**(8), 183–194, doi: 10.1111/cgf.12196.
60. BRIDSON, R., MARINO, S., FEDKIW, R. Simulation of clothing with folds and wrinkles. In *SCA '03, Symposium on computer animation : book of proceedings*. Switzerland, 2003, 28–36.
61. THOMASZEWSKI, Bernhard, PABST, Simon STRAßER, Wolfgang. Continuum-based strain limiting. *Computer Graphics Forum*, 2009, **28**(2), 569–576, doi: 10.1111/j.1467-8659.2009.01397.x.