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Three-dimensional simulation of warp knitted structures based on geometric unit cell of loop yarns

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Abstract

Warp knitted (WK) fabrics are typically three-dimensional (3D) structures, and their design is strongly dependent on the structural simulation. Most of existing simulation methods are only capable of two-dimensional (2D) modelling, which lacks of perceptual realism and cannot show design defects, making it hard for manufacturer to produce the required fabrics. The few existing methods capable of 3D structural simulation are computationally demanding and therefore can only run on powerful computers, which makes it hard to utilize online platforms (e.g. clouds, mobile devices, etc.) for simulation and design communication. To fill the gap, a novel, lightweight and agile geometric representation of warp knitting loops is proposed to establish a new framework of 3D simulation of complex warp knitted structures. Further, the new representation has great simplicity, flexibility and versatility and is used to build high-level models in representing the 3D structures of warp knitted fabrics with complex topologies. Simulations of a variety of warp knitted fabrics are presented to demonstrate the capacity and generalizability of this newly proposed methodology. It has also been used in virtual design of warp knitted fabrics in wireless mobile devices for digital manufacture and provides a functional reference model based on this simplified unit cell of warp knitted loops to simulate more realistic 3D warp knitted fabrics.

Keywords: Warp knitted fabric; 3D simulation; Geometric modeling; 3D loop model

Introduction

Warp knitted (WK) fabrics are composed of multiple layers of loops cross-linked together forming into 3D structures. Their simulations for virtue fabric design and manufacture of functional applications such as knitted garments and home textiles[1] have been the focus of knitting industry[2]. Various studies have attempted to use conjugate surface theory and 2D numerical methods to analyze WK structures. Most of existing computer-aided design (CAD) software can simulate WK fabrics in 2D with fairly good results, but they lack detailed representations of 3D crosslink structures[3] and therefore have difficulties in describing the complicated overlappings of yarns in the 3D structure of a loop sleeve. In addition, virtual design in mobile devices have been used in both flat and circular weft knitting industries, but has not yet been used in warp knitting[4]. 3D simulation of WK fabrics in a mobile device is a natural next step, and is therefore crucial and desirable for fast virtual design and digital manufacture of functional products in warp knitting industry.

For a successful 3D simulation of WK structures, the methods for modeling detailed structures of a warp knitting loop are the key and can be divided into two categories: empirical modeling and geometric modeling. Empirical models of a loop are constructed by both loop parameters and its mechanical model with empirically identified parameter values. In an empirical loop model proposed by Goktepe et al[5] for basic two-bar structures, the micrographs of these fabrics fabricated on a Raschel machine were measured to obtain the 3D configurations of the yarns inside the fabrics. A general loop model was established to simulate the 3D two-bar WK structures based on the analysis of real WK loop data. A Finite Element Method (FEM) for the analysis of the mechanical properties of 3D WK fabrics was proposed by Argyro et al[6], the WK fabric microstructures was modelled and an iterative method was used to optimize the geometric representation of the microstructures. Then, a 3D model of WK spacer fabric structures using non-uniform rational b-spline curves and surfaces was proposed by Zhang et al[7]. A rule-based system to compute the offsets of certain stitches is employed to simulate the stitches realistically according to the inclined fabric stitching. They used the migration rule of stitching to simulate the realistic stitching, the offset calculation formulae for any given point in the 3D stitch model was then derived. A FEM model of a 3D loop element and a sheet model of a metal WK fabric using the loop units were proposed by Xu et al[8] to predict the fabric's mechanical properties. The numerical results of the uniaxial tension analysis of the fabric were verified by experiments on metallic fabrics. These empirical models can clearly describe the loop morphology of WK fabrics, but they are neither suitable for most WK fabrics due to the limitations of the measurement ranges, nor can they be used for WK fabrics with complex structures.

A geometric model is a series of geometric shapes and relationships of yarns in a 3D WK fabric. It is used to calculate the geometric relations between the parameters of the yarn loops. In a dynamic explicit finite element model established by Duhovic et al[9] for simulating the geometric shape and the residual stress of a 3D WK fabric in the production process, each filament is represented by a series of connected rigid beam elements that undergo complex contact interactions with yarns, and the numerical simulation results are compared with experimental data to verify the model validity. A 3D loop structure model of WK yarns by using non-uniform rational b-splines was established by Renkens et al[10] to simulate the basic geometric shapes of warp knitting structures. An approach was then proposed to transform the basic structures into 3D states of slack fabrics in the presence of deformations. A parametric 3D loop model of WK structures is proposed by Zhang et al[11] to predict the loop geometry under the change of fabric processing parameters. Based on the process matrix of the WK structure and the internal stress analysis, an algorithm was developed to empirically link the process parameters to the 3D coordinate data points in the geometric model of WK loops. The model derived from interpolating fitting curves are used to describe the 3D geometry of WK loops. Li et al[12] established a parametric unit model of uniaxial reinforced WK composites to analyze fiber deformations caused by knitting yarns, for structural design and manufacture. At present, 3D simulation of WK fabrics is mostly on less-guide bar fabrics, while there are few studies on 3D simulation of complex WK fabrics such as multi-guide yarn and lace[13].

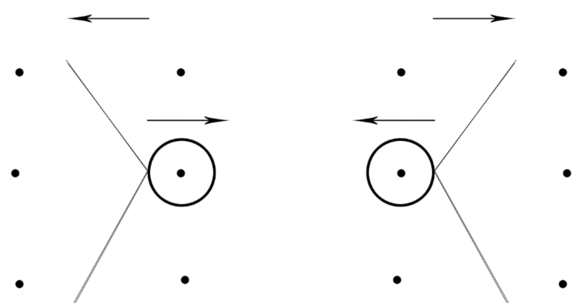
Although the geometric models discussed above can be used to describe the 3D space structure of yarn loops, they only focused on a single WK structure and did not incorporate production practices. Most of existing models are based on the assumptions that a yarn is composed of straight segments, which is inconsistent with the actual yarn shape; The other studies have assumed that models of a knitted yarn loop consists of a loop backbone and extension lines. The number of rows that the extension line crossed will cause a difference depending on the type of loops. This will lead to a more complex point selection scheme for the extension lines and non-smoothness of extension line connections. In addition, the existing methods are too computationally demanding to run on mobile devices and cause significant difficulties in data sharing, e.g. online.

In this paper, a novel 3D unit loop model incorporating TubeGeometry and Three.js in spline curves in FEM is proposed for geometrically modelling of 3D warp knitted structures. The 3D geometric model of the loop yarn is rendered using WebGL. The proposed model for knit loops and simulation methods intend to enable data sharing through online platforms easily. Furthermore, it is anticipated that this newunit model will provide a basis for further research, potentially together with other geometric representations such as spline surfaces, to simulate more realistic geometry of the yarn loops such as inclined stitches in real warp knit structure.

Modeling of 3D yarn loops in a warp knitting structure

Modeling of warp knitted fabric includes defining the type of yarn loops, the loop configuration, the loop path and the deformation of yarn loops.

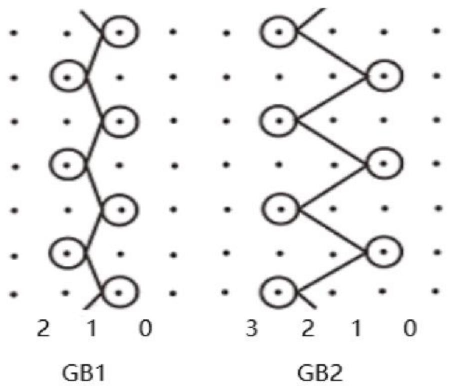
According to the rule of overlapping and underlapping of loops in a warp knitted fabric, many types of loops can be formed such as open loop, closed loop, weft insertion and warp repetition[14]. Before 3D modeling, it is necessary to determine the type of the loop according to the rule of yarn lapping and padding. For example, there are two types of closed loop, right closed loop and left closed loop, in which the lapping direction of the front and back of the needle is opposite. A right closed loop is formed when the overlap goes to the right and the underlap goes to the left as shown in Figure 1 (a); A left closed loop is formed when the overlap goes to the left and the underlap goes to the right as shown in Figure 1 (b). Therefore, the geometric shape of closed loops varies with the direction of the overlapping and underlapping.



(a) Right closed loop (b) Left closed loop

Figure 1. Types of closed loop

The loop configuration in a warp knitted fabric can be described by using the needle numbers (e.g., number 0, 1, 2, 3 in Figure 2) in a guide bar (GB), which carries the yarn in the knitting machine to specific needles to form the loop, to represent the loop lapping configurations. For example, the loop lapping structure of a warp knitted fabric made from a knitting machine having two guide bars (i.e., GB1 for the front guide bar and GB2 for the back guide bar in Figure 2) can be expressed as, laying-in digital (GB1:1-0/1-2// and GB2:2-3/1-0//), as shown in Figure 2.



GB1:1-0/1-2//; GB2:2-3/1-0//

Figure 2. Two loop configurations in a warp knitted fabrics made from knitted machine having two guide bars (or needle bars)

We can also use a 3D matrix R of laying-in digital in each needle to define yarn loops formed in a warp knitted structure. The yarns with the right end are numbered as the starting points, so that the first row is circled on the first needle and the second row is circled on the second needle[15]. A loop is described by using the needle number where the loop formed. The needle number in each row is represented by the larger of the two digits in the row. From this, we use a 3D matrix R of the needle numbers to indicate yarn loop configurations in a warp knitted structure:

$$\mathrm{R} = \begin{bmatrix} r_{1,h,1} & \cdots & r_{I,h,1} \\ & r_{i,j,1} & \\ r_{1,1,1} & & r_{I.1.1} \end{bmatrix} \cdots \begin{bmatrix} r_{1,h,\mathrm{k}} & \cdots & r_{I,h,\mathrm{k}} \\ & r_{i,j,\mathrm{k}} & \\ r_{1,1,\mathrm{k}} & & r_{I.1.\mathrm{k}} \end{bmatrix} \cdots \begin{bmatrix} r_{1,h,\mathrm{w}} & \cdots & r_{I,h,\mathrm{w}} \\ & r_{i,j,\mathrm{w}} & \\ r_{1,1,\mathrm{w}} & & r_{I.1.\mathrm{w}} \end{bmatrix}$$

Where w is the total number of needles which represents the width of the loop structure, $r_{i,j,k}$ is the loop 's needle number in the needle of i_{th} guide bar, j_{th} row, k_{th} wale.

For example, the loop structure in the parameter format, GB1: 1-1/1-2//, can be described by using the matrix R having the component values, $R_{1,1,0}=1$, $R_{1,1,1}=1$; $R_{1,2,0}=1$, $R_{1,2,1}=2$. So does GB2: 1-1/2-2//, the component values of the matrix R are, $R_{1,1,0}=R_{1,1,1}=1$, $R_{1,2,0}=R_{1,2,1}=2$.

The drawing of a yarn can be represented using a 3D thin and long tube in computer graphic simulation models. The starting and ending points of such yarn loops here refer to the starting and ending points of the trajectory when drawing the loop yarn diagram. After R is obtained, the direction of the extension line can then be determined.

The loop path is represented by a 3D spline curve passing through the centre of the yarn. To capture the volume, the spline curve is inflated into a 3D tube uniformly. Further, to simplify the representation for computation and rendering later, we assume a piece-wise linear property of the yarn and use a series of straight tube segments for approximation. TubeGeometry in Three.js is used to form 3D spline curve. The number of yarn segments needed for the whole loop path is automatically computed based on an area criterion, so that a loop path is represented by a chain of identical tube segments (in terms of their lengths and radii). Generally, the longer the path is, the more the tube segments are needed. As the number of tube segments increases, a better approximation to the original yarn is obtained. In addition, the closed attribute determines the end-to-end connections of the tubular segments. Therefore, the model simplifies the steps to build a spline curve in TubeGeometry which provides multiple attribute parameters to draw a smooth loop consisting of number of tubular segments having adjustable sizes[16]. We combine the vertices of all the yarn loops in the horizontal direction of a segment of the guide bar into a group, on the basis of the characteristics of the warp knitted fabrics, to make the path of a guide bar in a smooth curve.

Given the loop type, loop configuration and loop path, a model of the 3D geometric loop structure is constructed to obtain the 3D structures of warp knitted fabrics. The geometric model of the loop proposed also has a unique feature: it does not include any extension line. Instead, it solely uses the backbone of the yarn loops, the end point of the lower extension line and the starting point of the upper extension line. The backbone of each yarn loop is identical without distortion. The pick point of each loop consists of the starting and ending points of the extension line in the row of the loop trunk, and it automatically connects the middle extension line to realize any connection of the loop[17]. After judging the type of loop according to the rule of lapping, the geometric shape of each loop can be simulated by 3D modeling. Our succinct and modulated representation can be used to conveniently describe some basic loop types which are universal in many fabrics, shown in Table 1 and Table 2. The simplicity of the representation enables us to describe complex warp knitting structures easily and effectively.

Table 1. The loop types and their 3D models included in this modelling

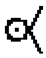
Type of yarn loops	Three-dimensional model
Right closed loop 	
Left closed loop 	
Left open-ended loop 	
Right open-ended loop 	
Right opening chain 	
Left opening chain 	
Right laying in 	
Left laying in 	

Table 2. Component values of the matrix R corresponding to the extension lines of a few different types of open loops shown in Table 1

Direction of the loop	Condition	Loop type
Right open	$R_{i,j,0} \geq R_{i,j-1,1}$ and $R_{i,j,1} \leq R_{i,j+1,0}$	 or 

	else	
Left open	$R_{i,j,0} \le R_{i,j-1,1}$ and $R_{i,j,1} \ge R_{i,j+1,0}$	 or 
	else	

where the loop opens to the right if R is the small digit in the current row; the loop opens to the left if R is the large digit in the current row, and else represents a situation where the former condition is not satisfied. In this way, the extension line of the open coil is classified.

Modelling the 3D structure of a warp knitting structure

A simplified geometric unit cell model of a warp knitting loop

The performance of 3D simulation of a warp knitted fabric depends on the quality of the loop structure model. In order to establish a concise simulation system for complex warp knitting fabrics, the structure of a warp knitting loop yarn with multiplex geometric shapes is represented by using a simplified unit cell geometric model as shown in Figure 3.

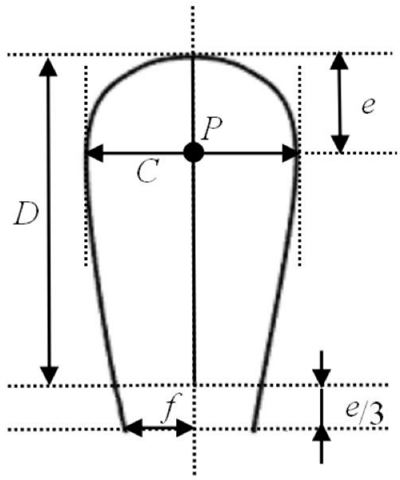


Figure 3. A simplified geometric unit cell model of a loop

where C is the total width of the loop, P is the center point of the width of the loop, D is the height of the loop segment where the loop is not overlapped by previous loops, the upper part of the yarn (the part above the total width of the loop) is a circular arc and e is the height of the circular arc, f is distance between bottom endpoint and the center line, and we implement the loop model based on both the loop structure characteristics and the multipoint motion pattern[18].

Positioning a loop yarn in the coordinate system of a warp knitting structure

After defining the geometric shape of each loop in a warp knitting structure, the next step is to determine the position of a loop yarn in the coordinate system of a 3D warp knitted structure. The position of a loop is represented by the position of the center point of the loop width (*P* in Fig.3), then the points on the loop are locally represented in a local Cartesian coordinate system with the origin at $P(P_x, P_y, P_z)$. Given a square 3D warp knitting structure without deformation shown in Figure 4, we establish a global 3D Cartesian coordinate system with the origin *O* at the mid-point of the square, with the z axis pointing into the screen.

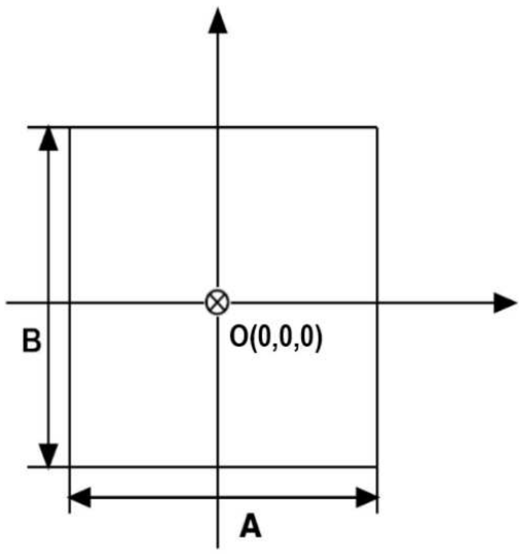


Figure 4. Planar area coordinates

In Figure 4, *A* is the width of the knitted fabric structure in terms of integral multiples of the number of loops, *B* is the length of the knitted fabric structure in terms of integral multiples of the number of loops, and the increment of horizontal and vertical coordinate of the loop position point are the width and height of the loop (e.g., *C* and *D*) respectively, the symbol ⊗ represents the z axis in inward direction. In this coordinate system, the center point, $P(P_x, P_y, P_z)$, of the width of a loop, whose position is determined by $R_{i,j,k}$, can be computed in the equation as follows:

$P_x = C * (A / 2 - k + 1) - C / 2 - (R_{i,j,k} - 1) * C$

$P_y = D * (j - B / 2 - 1) - e$

$P_z = 0$

where $k \in [1, A]$, $j \in [1, B]$, $R_{i,j,k}$ is the needle number (or needle position) of the loop formed around the needle in the i_{th} guide bar, j_{th} row, k_{th} wale. Thus, each loop can calculate the plot position based on the coordinates of central point $P(P_x,P_y,P_z)$.

Migration and connection of the loop yarns

As shown in Fig 5, the structure of a warp knitted fabric can be represented by a matrix of multiple loops connecting with their adjacent loops through both their lower extension lines and upper extension lines. The shape and direction of the loop extension lines depend on the positions of the loop and their adjacent loops. The connection of the loop with its upper and lower loops can be realized as long as the coordinates of the starting and end points ($P_0(x_0, y_0, z_0)$ and $P_1(x_1, y_1, z_1)$) of the extension lines of the loops in relation to the coordinates of the center point of the width of the current course loop, $P(P_x, P_y, P_z)$, are known. Take the left closed loop as an example, the shape and the points of the extension line are shown in Figure 5.

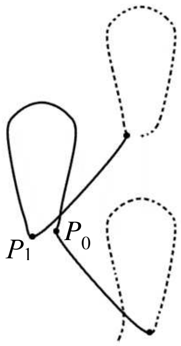


Figure 5. The data point of underlap

where P_0 is the starting point of the next course underlap and P_1 is the end point of the last course underlap. In order to form a closed loop and place the extension line forward, the Z coordinates of the two points are determined by the position of the guide bar. The specific coordinates of the two points are as follows:

P_0: $x_0 = P_x + f + d$, $y_0 = P_y - D + 2e / 3$, $z_0 = P_z + d + (I - i) * d$;

P_1: $x_1 = P_x - f + d$, $y_1 = P_y - D + 2e / 3$, $z_1 = P_z + 2*d + (I - i) * d$;

where P_x, P_y, P_z are the coordinates of the center point of the width of the loop, $P(P_x, P_y, P_z)$; d is yarn diameter which is calculated from yarn linear density values, I is the total number of guide bar; D, e and f are defined in Figure 3. From the above formula, we can see that both z >0, the separation of the extension line and the loop trunk not only guarantee the coverage relationship of the extension line but also avoid the embedding phenomenon[19]. The other loops are drawn based on the translation of P_0 and

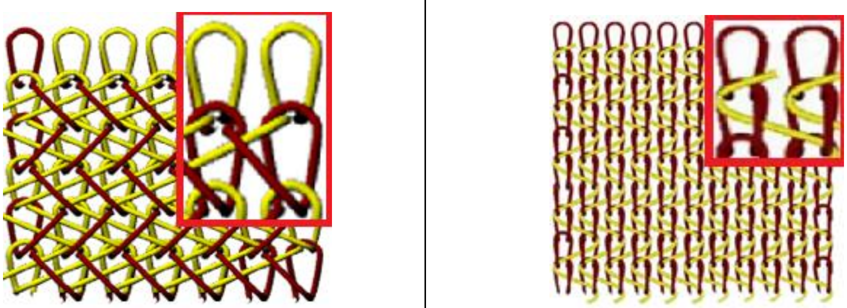
P_1. After the points of the extension lines were selected, the simulation results of warp knitted structures is shown in the Figure 6 assuming no deformation. In addition, different types of loops can be automatically constructed similarly and this will simplify the 3D simulation of complex warp knitted structures.

Results and discussions

The 3D simulations of four types of fabrics produced using our method are shown in Figure 6. They cover several typical fabric types. These four fabrics include single-stitch bed low-comb fabric and double-stitch bed spacer fabric, which are mainly used to form various knitted fabrics by looping with weft lining. Figure 6 (a) shows a simulation of a double guide bar locknit fabric. The laid-in organization is GB1: 1-0/1-1-2///, GB2: 2-3/1-0///; Figure 6 (b) shows the simulation of chain laying-in fabric. The laid-in organization is GB1:1-0/0-1//, GB2:0-0/2-2//; Figure 6 (c) shows two comb mesh fabrics but with no connection between adjacent loops. If no extension line is connected between adjacent coils, a mesh will be formed. The laid-in organization is GB1:1-0/1-2/1-0/2-3/2-1/

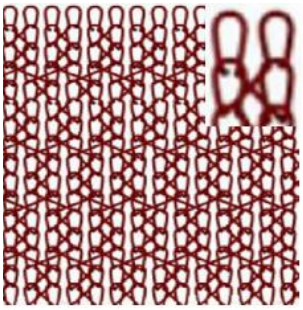
2-3//, GB2: 2-3/2-1/2-3/1-0/1-2/1-0//; Figure 6 (d) shows a simulation of a three guide bar square fabric which contains loop types including closed, open-ended and chain stitch. The laid-in organization is GB1:1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0/1-2/2-1/1-2/2-1/1-2/2-1/1-2/; GB2:1-0/1-2/

2-1/1-2/2-1/1-2/2-1/1-2/1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3//;GB3:2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0/2-3/1-0//.

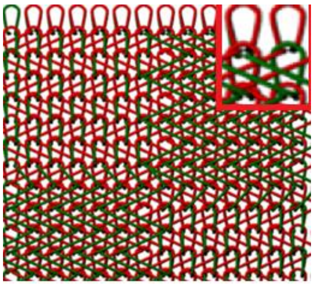


(a) Locknit

(b) Chain laying-in



(c) Two-comb mesh



(d) Square of three-guide bar

Figure 6. Simulation of the surface construction of four warp knitted structures

Figure 6 is the simulation of 4 kinds of fabrics produced by our method, while Figure 7 is the fabrics produced by warp knitting machine according to the simulation result of Figure 6 (a, b, c, d). The comparison results of production object and simulation show the validity and accuracy of our model.

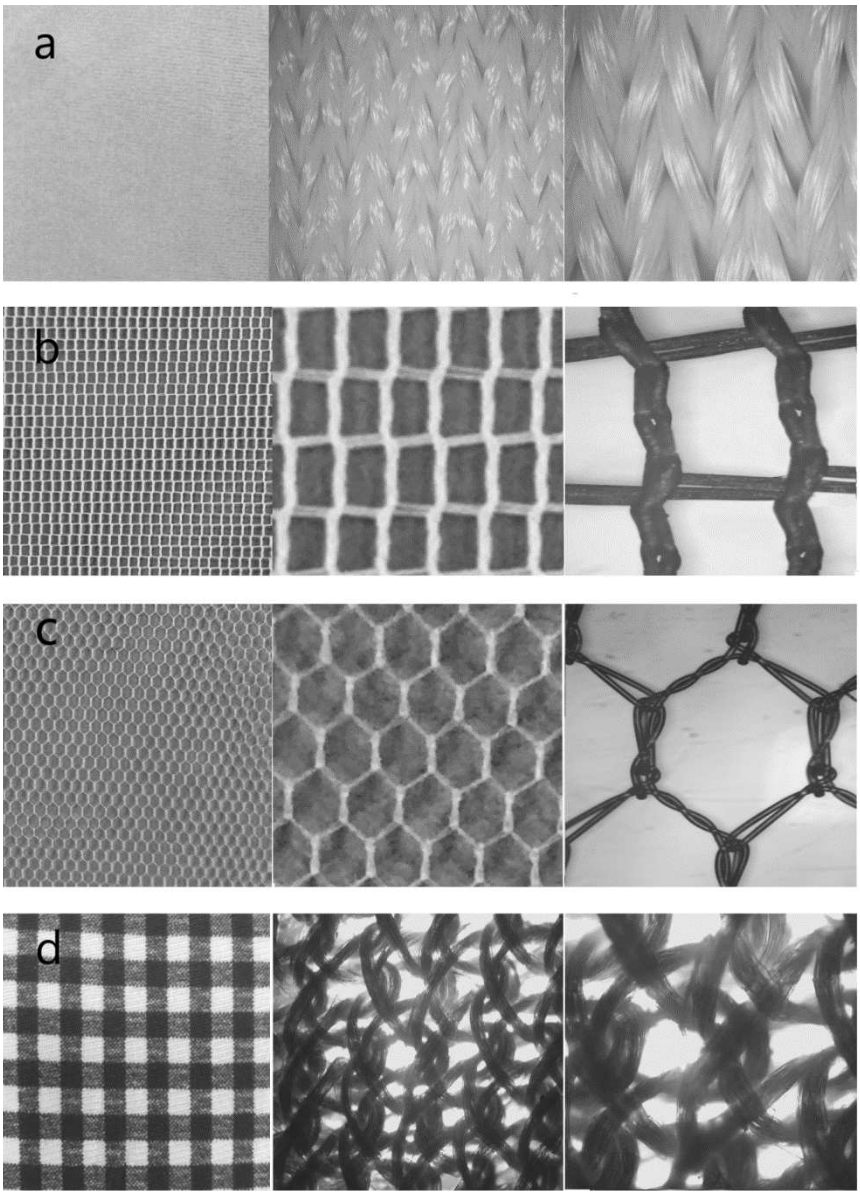


Figure 7. 2D images of three-dimensional warp knitted samples corresponding to Figure 6

The proposed model can be rendered in OpenGL, WebGL and other platforms. For example, TubeGeometry and Three.js can be used in 3D simulation of warp-knitted fabrics in WebGL. After illumination and rendering, the 3D mesh fabric is shown in Figure 8. It is zoomed in to the maximum using orbitcontrols.js. TubeGeometry makes the complicated definition of extension lines in previous software unnecessary and thus makes the model much simplified in simulating different types of loops such as acrylic yarn and blended yarn[20]. According to the loop type, the number and positions of 3D data points describing the path of the loop are determined to establish the relation between the number of guide bars and the yarn diameter[21]. We have improved the point selection of the previous loop to optimize the data point selection of the current one, including the point of the main stem of loop, the end point of the previous course underlap, and the beginning point of the current course underlap, to achieve arbitrary connections of the loop.

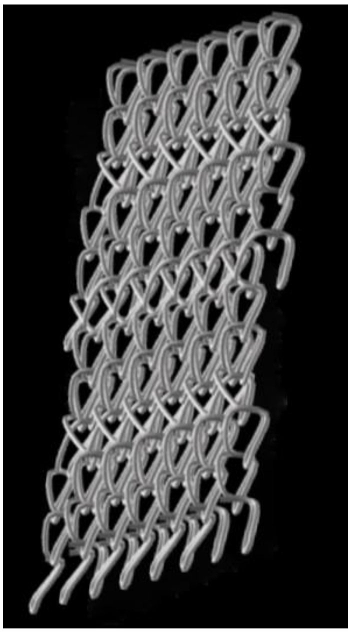


Figure 8. A example of 3D simulation of mesh fabric

The novel geometric model and approach introduced in this paper is capable of 3D simulation of WK fabrics with complex structures for the virtual design of functional WK products. Moreover it has been successfully used as a commercial software in mobile devices. The approach is applicable to most knitting structures, and it makes 3D simulation of knitting fabrics much simpler. However, it is noted that the geometric unit of loop yarns proposed is a model without considering factors such as inclined stitches as well as variations in yarn tensions, twists and mechanical properties, and unevenness. These limitations will be addressed in the future work.

Conclusions

We have proposed a new framework for fast and lightweight 3D WK fabric simulation. To this end, a novel geometric unit model of a WK yarn loop is first proposed. Based on it, a fabric model is established for the simulation of 3D WK fabrics with complex structures. The description of different types of loops using spline curves has been proposed to simulate various WK structures. The discretization for constructing loop segments into a specific loop is optimized. We have shown that the proposed method is capable of simulating intricate WK fabrics for its design and manufacturing.

Moreover, thanks to the lightweight nature of the method, it has been implemented, tested and successfully used in the real world on an online platform where the data sharing, co-design and pipelining are massively simplified. In the future, we will look into integrating our method with existing CAD software so that it can fit into existing pipelines and boost the overall performance through the whole life-cycle of fabrics, from design to manufacturing.

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