Advances in the CAD Simulation of Textile Yarns

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ABSTRACT

A project aimed at the 3D simulation of textile yarns from technical specifications was begun in 1993 and attracted support from both industry and research councils to enable the formation of a multi-national team of researchers to come together in the UK. Considerable progress has been made particularly in the simulation of knitting yarn and plain knit fabric. In recent times the team has tackled the problem of simulating mixture coloured yarns sometimes called melange. This has necessitated a more complicated model of yarn structure based on queuing theory which is outlined at the end of the paper. References are provided for readers who wish to learn more of the various theories and models that have been used throughout the course of this project.

Keywords: Yarn, Modelling, CAD, Simulation, 3D, Queuing Theory

1. Introduction

Despite over sixteen years of endeavour, the CAD simulation of accurate textile yarn 3D simulation project remains work in progress and due to the complexity of the subject and the reactionary nature of the industry it will probably continue as such for some time to come. The different approach taken by this group can be summed up quite simply as follows:

When a fabric is to be designed and then produced it is first necessary to choose suitable yarn with the required aesthetic and mechanical properties. It is therefore logical that if an accurate computer simulation of a fabric is to be produced, we should begin with the accurate simulation of the component yarn (Cassidy, T. & Grishanov, S., 2008).

As with all simple statements of concept, the implications of this statement are far reaching. Only by getting CAD for yarn simulation right will CAD for fabric simulation be accurate and consequently CAD for apparel simulation will become the useful and necessary tool that it promises to be.

2 Background

A question to be considered at this stage is why those who developed the early CAD systems choose to start at the fabric stage and not with the same building block used by fabric producers – the yarn. The answer is quite simple. Symbolic notation methods for fabric structures were available and commonly used throughout the textile industry for over two hundred years before the advent of personal computers. Indeed, the Jacquard loom is considered by many as the predecessor of the computer and operated a complex shedding mechanism in response to a manually prepared notation. Early developers, therefore, already had manual simulations to use as a base reference. No such notations were available for yarn structures and their mechanical properties were relatively poorly understood despite the sterling efforts of researchers such as Treloar, Hearle, Martindale, Goswami and many others. It is sobering to think how much progress they might have made had they had access to modern high-powered computers. As it was much of this work went unheeded but the existing body of work provided a starting point for the YarnCAD team as it was first formed through a grant from EPSRC (Engineering and Physical Sciences Research Council) in 1993.

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3 Early Stages

The aim of the project was to make a computer model which would accurately simulate a flexible fibrous assembly, such as yarn in a three dimensional form, and had sufficient accuracy to allow it to be incorporated into a knitted or woven fabric simulation. Consequently a great deal of complicated mathematics was involved; for the reader who wishes to study these carefully references will be given at each stage but in this paper only an outline will be given.

3.1 Yarn Appearance Simulation

Much of the early thinking about how to accomplish the simulations was given in a conference paper (Liu et al., 1995) though a more accurate explanation including the use of a compression model to improve the accuracy of the simulations is given in Grishanov et al. (1997a).

It was necessary to generate the strand shape correctly and therefore it was assumed that the strand had a constant linear density (count) along its entire length. In this way the simulated cross-sectional shape will be the same throughout its length and the centre line of a strand will maintain a constant distance from the centre of the yarn twist. Each strand in a yarn will follow a helical route along the axis of the yarn according to the established geometrical models (Hearle et al., 1969; Hearle, 1989; Goswami et al., 1977).

A quadrilateral-mesh method was employed to generate a wire frame model of the strand surface. In this model each quadrilateral is defined by 3D co-ordinates of four vertices as shown in Figure 1. Each quadrilateral is in turn divided into two triangles; each triangle is one facet.

The facets are formed from the neighbouring vertices in the array. Therefore, an array of M rows and N columns produces a 2(M-1) by N-1 mesh of triangles. In Figure 1, M is 4 and N is 5. In creating the mesh several aspects had to be pre-defined.

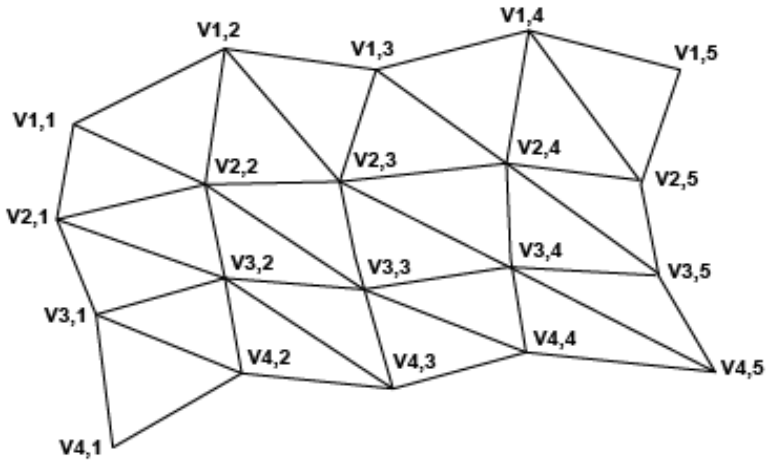


Fig. 1. A triangular mesh

3.2 The Mesh Size

The size of mesh directly affects the smoothness of the surface generated and is also an important factor influencing the texture simulation of the surface. Theoretically, the smaller the triangles in the mesh are, the smoother the surface will be. To a certain extent, a smoother surface is closer to the reality of the majority of yarn appearances. However the mesh size is practically restricted by the hardware used such that when the mesh size is defined too small, the array dimension would be too big for keeping all the vertex data in the memory or even if there was no problem for the array dimension, the speed at which the surface is created would become unacceptable. A compromise is therefore necessary between the accuracy of the strand shape and the display effect. Another aspect to be taken into account is that the dimensions of the pixels on the computer monitor are greater than the typical diameter of individual fibres in the yarn. Therefore it would not be possible to display the fibrous structure of the yarn on a 1:1 scale.

3.3 The Cross Section of the Strand

In the case of conventional multi-strand yarns, each strand is simulated as solid helicoids whose cross-section in the tangent direction is a circle, which is an accepted approximation in yarn modelling. Naturally, the intersection of the plane, which is perpendicular to the axis of the multi-strand yarn, with the helicoids produces a kind of ellipse; the major and minor axes of this ellipse depending on yarn linear density and twist level. In order to provide more realistic simulations it was quickly realised that the cross-sections could not be circular and that a study would have to be carried out in order to define how strand cross-sections changed with the degree of twist and other factors.

3.4 The Vertex Array

The vertex array is created to contain the actual x-, y- and z-coordinates of all the vertexes on the mesh surface. In order to start the simulation of the strand surface, the vertex array must be assigned the 3D coordinates which are generated from the initial definition, rotation and translation. Figure 2 shows a mesh surface.

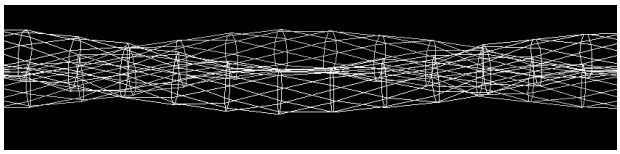


Fig. 2. Mesh surface

3.5 Colour

Colour rendering was used to reveal the yarn texture. When colours are initially assigned to each strand, they are called intrinsic colours. In order to obtain more realistic images the intrinsic colours are organised to pass four stages of rendering as shown in Figure 3.

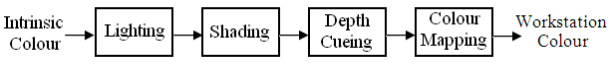


Fig. 3. Colour rendering

Together with the triangular facets arrangement, colour rendering was also used to simulate the orientation of the fibres of which the strands were comprised.

3.6 The YarnCAD System

Using the strategy described in Section 1 above, the first version of the YarnCAD system was produced using C language with a PHIGS graphics routine on a SUN platform. At that time (1990s) the UNIX operating system was considered best for simulation work of this type. As we will see, this had to change. Based on the geometrical model, the input specifications of the yarn included: yarn type (spinning system); yarn twist content and direction for both single and plied yarns; number of strands, linear density of strands and specific volume of fibres. When these specifications were input into the system the geometrical structure of the yarn was converted into an array of triangular facets representing the surface of the strands involved. The data of the vertex coordinates were passed onto the yarn modeller to produce the simulated yarn appearance with a simulated yarn texture as shown in Figure 4.

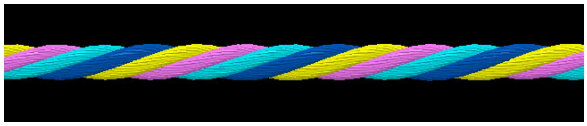


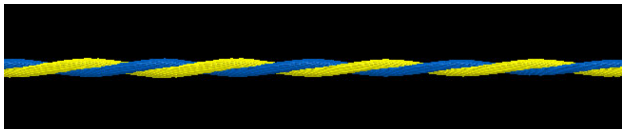
Fig. 4. Simulated image of a 4-plied yarn

This ended the first stage of YarnCAD development. What set this work apart from anything else that existed at that time (1990s) was the ability to simulate from manufacturing specifications and to be accurate when compared to the real yarn produced from the same specifications. Also the system was able to manipulate the simulated image using the arrow keys on the keyboard or the directional buttons on the interface to show the true 3D nature of the simulation.

4. Further Development of Yarn CAD

A second grant was provided by the Engineering and Physical Sciences Research Council to enable further development of the system. Changes occurred within the team of researchers and in particular there was a strengthening of the mathematical modelling capability of the team enabling the development of more complex and accurate fundamental mathematical models underpinning the system.

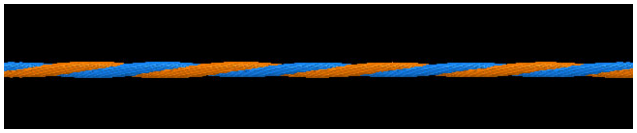
It was realised that although single yarns can be successfully simulated using circular yarn cross-sections, the strands in the twisted yarns are flattened by the lateral compression forces resulting from yarn tension and bending of individual strands into a helical shape. A theoretical model of yarn compression was developed (Grishanov et al., 1997a) and tested against real yarns of varying twist levels. Many samples of the latter were painstakingly prepared by encapsulating different twist level yarns in a resin after carefully placing yarn samples into specially designed capsules. Cross sections could then be cut and the varying levels of strand compaction observed and measured. The results were then compared with the predictive model results; an acceptable level of correlation was obtained and therefore the model was incorporated into the YarnCAD system (Bradshaw et al., 1998). Figure 5 below shows the same count of yarn at two different twist levels and two different levels of yarn tension to demonstrate the effect of the compression model.



(a) 100 tpm folding twist



(b) 130 tpm folding twist



(c) 100 tpm folding twist, increased tension

Fig. 5. Effect of yarn tension and twist level on yarn appearance

For an additional degree of realism the fibrous structure of the simulated yarn was generated as a corrugated surface of revolution with the diameter changing along the yarn length according to the spectral characteristics of the unevenness of the real yarn (Grishanov & Harwood, 1999).

Towards the middle of 1997, the team realised that if the system were to be acceptable to the industry in the future then the platform would have to change from Unix to the more commonly used Microsoft operating system.

Collaborators in the project at this stage included CiS Graphik & Bildverarbeitung Gmbh of Germany. This company had a commercial CAD system which provided excellent 3D fabric simulations and allowed the input of yarn irregularity/unevenness values. However their yarn simulations were achieved mainly by scanning and did not have the realism of YarnCAD nor the possibility to create from manufacturing specifications. CiS also used the Unix platform and decided not to swap to Microsoft. Unfortunately they no longer appear to be in this market.

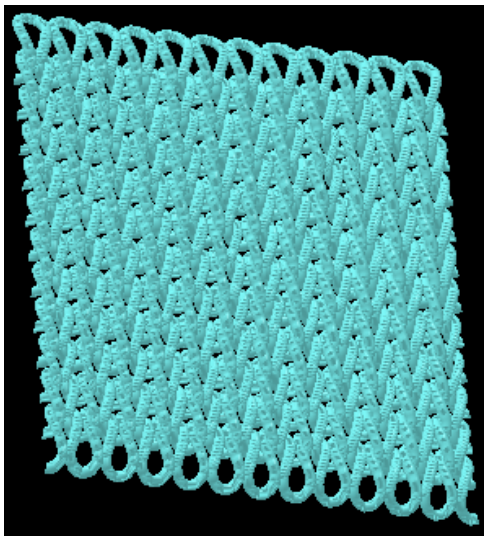
Having switched the system to the Microsoft platform, the team began making presentations to designers from industry to get their feedback; one valuable lesson from this was that the system would never be acceptable to the industry unless the yarn could be knitted into an accurate swatch and therefore a knitting module was added to the software by Dr. Grishanov (Grishanov & Harwood, 1999).

This module required information on the bending characteristics of the yarn and thus another predictive model was required which was tested against the results from a KES-F bending tester for real yarns. This model was successfully generated and Figure 6 shows the plain knit swatch of simulated yarn in two views. In many ways this is the most exciting part of any demonstration of the system and proves the true 3D nature of the simulations. Also, in many cases the designer may use the reverse of a knitted structure as this may have the most desirable effect. A 3D model of plain weft knit structure was presented in Kyosev, Agelova and Kovar, (2005) but the yarn model used was underdeveloped.

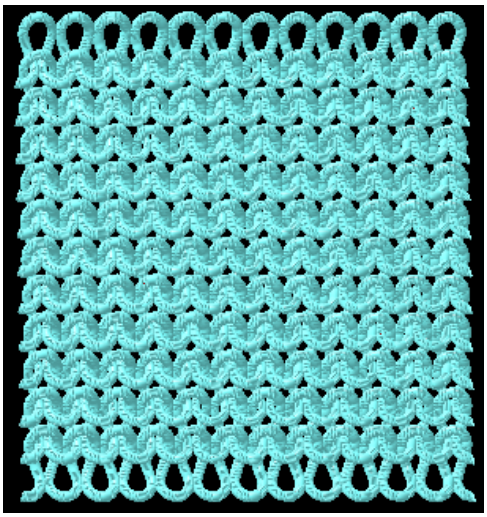
Further consultations with textile technologists and product development teams have shown that there is a specific type of yarn, i.e. melange yarn, which is often difficult to design and manufacture to the specified colour.

Melange or mixture yarns are made by the mixing, within the same strand, of fibres of varying colours from as few as two or three to twelve or

more colours. Many attempts have been made towards solving the problem of providing a mathematical model which would be able to predict the colour of a yarn from its technical parameters (Townend et al., 1964; Bishop et al., 1991; Sokkar et al., 1992) but as yet there has been limited success.



(a) 3D view of fabric technical face



(b) Technical back of fabric swatch
Fig. 6. Examples of knitted swatches

Even fewer attempts have been made on the development of industrially sound computer-aided design systems for melange yarns. One example was a BRITE-EURAM-funded project entitled 'Computer Aided Simulation of Textile Special Yarns for the Spinning Industry'. The yarn simulations produced by this computer software however, have disadvantages such as the adoption of a 2D approach to the simulation of yarn structure which will not give realistic yarn images. It will be difficult if not impossible, to incorporate 2D yarn images into a 3D fabric simulation. Also the images produced fail to present the yarn colour composition correctly.

In 2003, grants were awarded by the Engineering and Physical Sciences Research Council to enable teams at De Montfort University and the University of Leeds to collaboratively investigate the structure dependent colour properties of melange yarns. The aim of the project was to generate a new model of yarn structure which would enable the prediction of colour of melange yarns to be made from yarn technical specifications, colours and percentages of blend components. A neural network approach for predicting yarn cross sectional colour was presented in Shams-Nateri, Amirshai and Latifi (2006). Yet this does not model the behaviour of fibres in the yarn structure and does not attempt to apply the results to 3D yarn simulation.

5. Modern Approaches to Yarn Structure Modelling

At the early stages of the development of the YarnCAD system the 3D image of yarn was presented as that of a solid rod. The task of predicting colour of melange yarns required a much more detailed model to be generated which would consider the spatial position of all individual fibres in the yarn. The main difficulties were to take into account fibre migration in the yarn body and the dual nature of the yarn structure which is a continuous product made from discrete fibres. The theoretical foundation for resolving this problem was developed in a paper by Grishanov et al. (1999). This paper suggested a new method for modelling the path of individual fibres through the yarn body and all essential features of a yarn structure including fibre migration, fibre distribution over the yarn cross-section, yarn unevenness and hairiness. It was found that the process of fibre migration can be considered as a Poisson process. In this way each elementary event of fibre migration does not depend on the previous migrations but only on the current combination of factors which determine the direction of fibre migration.

This new concept was further advanced in a recent

publication (Siewe et al., 2009) where queuing theory is used for a detailed analysis of the behaviour of all fibres in the yarn and fibre distribution over the yarn cross-section.

5.1 Basics of Queuing Theory

Queuing theory is a mathematical study of queuing systems. A queuing system models a waiting line where customers queue to receive a service. Most of us are familiar with the concept of queues; they exist all around us in daily lives, whether in supermarkets, at petrol stations or banks. Typically, a queuing system has one *service centre* and a *waiting room* (a queue) of finite or infinite capacity. The service centre has one or more servers. Customers from a population or source enter a queuing system to receive some services. Upon arrival, a customer joins the waiting room if all servers in the service centre are busy and waits until a server is available. When a customer has been served, he leaves the queuing system.

Kendall (Baskett et al., 1975) proposed a standard notation A/B/C/D/E for classifying queuing systems, where A is the inter-arrival time distribution, B is the service time distribution, C is the number of servers, D is the system capacity (i.e. the maximum number of customers which can be accommodated in the system), and E is the population size. The symbols traditionally used for A and B are M (for exponential distribution), D (for deterministic distribution) and G or GI (for general distribution). A queuing system of infinite capacity (i.e. D = ∞) and infinite population size (i.e. E = ∞) is denoted as A/B/C. For example, an M/M/1 queuing system has an exponential distribution for inter-arrival time, an exponential distribution for service time, one server, infinite capacity and infinite population size. Because the inter-arrival time and the service time are exponentially distributed, an M/M/1 queuing system is a *markovian queue*.

A finite number of M/M/1 queuing systems can be interconnected into a network in which customers who have been served in one queuing system can move to another queuing system. In a Jackson open network of M/M/1 queuing systems (see Figure 7) new customers arriving from outside the network join a queuing system i according to a Poisson process with rate λ_i^0. Having been served at the queue system i, where service time is exponentially distributed with parameter μ_i, the customer either leaves the network with probability p_i^0, goes to the queuing system j with probability p_{ij}, or re-enters the same queue with probability p_{ii}.

Based on these probabilities, the dynamics of the network is modelled by a number of equations that are detailed in Baskett et al. (1975).

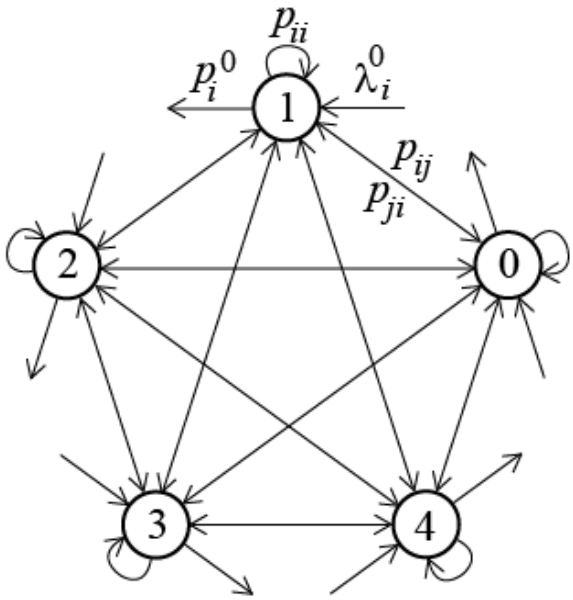


Fig. 7. An open network of queuing systems

The following sections explain how this theory was used in Siewe et al. (2009) to model the structure of melange yarns.

5.2 Yarn Cross-section Model

The model of yarn cross-section described by Morris et al. (1999) and Grishanov et al. (1999) was used, where each yarn cross-section is represented as a set of K concentric circular ring zones around the yarn centre. As depicted in Figure 8, the ring zones are assumed to have identical width d, large enough to accommodate fibres of specified average diameter and standard deviation. Each ring zone is divided into a fixed number of virtual locations (VLs) represented as circles of the same diameter d.

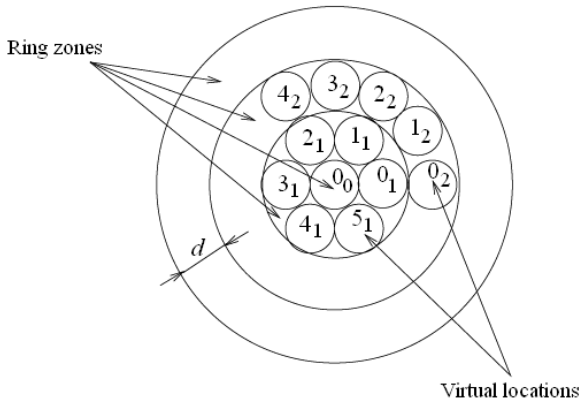


Fig. 8. A model of yarn cross-section

The ring zones are numbered from 0 to *K*-1 starting from the yarn centre and progressing towards the yarn surface. Ring zone 0 is situated at the yarn centre and consists of exactly one VL. A ring zone *i*, $1 \le i < K$, contains $z_i = \lfloor 2\pi i \rfloor$ VLs (i.e. the greatest integer less than or equal to 2 *i*). In this way ring zone 1 contains six VLs, ring zone 2 contains 12, ring zone 3 contains 18 and so on. The virtual locations of each zone *i* are numbered counter-clockwise from 0 to z_i-1 and the virtual location 0 is centred on the *x*-axis as illustrated in Figure 8.

In the queuing model of a staple yarn structure (Siewe et al., 2009), each virtual location is represented by a queuing system and each fibre is modelled by a customer. The migration of a fibre from one virtual location to a neighbouring virtual location is associated to the movement of a customer from one queuing system to another as discussed in the following section.

5.3 Queuing Model of Yarn Structure

The structure of the yarn is modelled by a sequence of cross-sections where each of them has a number of virtual locations arranged in concentric circular ring zones as described in previous sections. Fibres that constitute the yarn body occupy a fraction of all VLs available at any given cross-section according to the fibre packing density distribution. At any given time each VL can be occupied by not more than one fibre according to the 'one fibre – several locations' principle introduced by Grishanov et al. (1997b). Since it was found that fibre migration can be assumed to be a Poisson process Grishanov et al. (1999), the migration distances are exponentially distributed. The spacing between the cross-sections along the yarn axis coincides with the migration distance where fibres enter or leave the VLs that they occupy (see Definition 3.3, Siewe et al., 2009).

It is assumed that the arrival of new fibres into the yarn structure is also a Poisson process and hence the distances between the fibre leading ends are exponentially distributed but independent of the migration distances. Newly arrived fibres are allocated to virtual locations on a 'First Come First Served' principle. The behaviour of fibres from the point of their arrival is governed by a specific probability distribution which for each fibre determines the direction of its migration. After a series of migrations fibre terminates. For some fibres this may happen in the outermost circular zone in which case such fibres form the yarn hairiness and so do the fibres that start in the outermost zone. The fibre length is assumed to be distributed normally with known average length and standard deviation.

The combination of these two processes, i.e. fibre arrival and termination where the latter is affected by the fibre length distribution, causes the change in the number of fibres present at any given yarn cross-section and in this way provides a model for yarn unevenness. In fact, it is possible to predict the level of yarn unevenness from the distribution of fibre length and the distribution of the distances between leading fibre ends (Grishanov, 2009, pp. 90-93).

The yarn structure formed in this way is considered to be continuous so that there are infinitely many fibres involved. Using these assumptions, the staple fibre yarn structure was modelled as a Jackson open network of queuing systems where each queuing system represents one virtual location (Siewe et al., 2009).

Figure 9 shows a simplified model for a yarn with three ring zones. In this model zone 0 has one virtual location labelled as 0_0, zone 1 has six VLs from 0_1 to 5_1, and zone 2 has 12 VLs from 0_2 to 11_2. There is a clear correspondence between the queuing system and the yarn structure model. Each VL corresponds to a queue, fibres correspond to customers, the distance between fibre leading ends is the time interval between customers' arrival to the queue, fibre migration is the movement of customers between the queues,

the portion of fibre length in the same zone between successive migrations is the service time, and the total fibre length is the total time a customer spends in the network of queues.

There are few specific points to be taken into account when applying the queuing system model to the staple fibre yarn. In the case of general queuing systems a customer can move from any queue to any other queue. The yarn, however, has a layered structure; the fibre therefore cannot migrate from zone 0 to zone 2 without first passing through zone 1. In a similar way, fibre cannot migrate between VLs 0_2 and 2_2 without first passing through VL 1_2. Therefore in Figure 9 there are no links between any VLs which are not immediate neighbours. Furthermore, each zone in the yarn has a rotation symmetry. For this reason, for example, virtual locations 0_1 and 5_1, 0_2 and 11_2 are neighbours (see Figure 8); this is reflected by the link between the VLs shown in Figure 9.

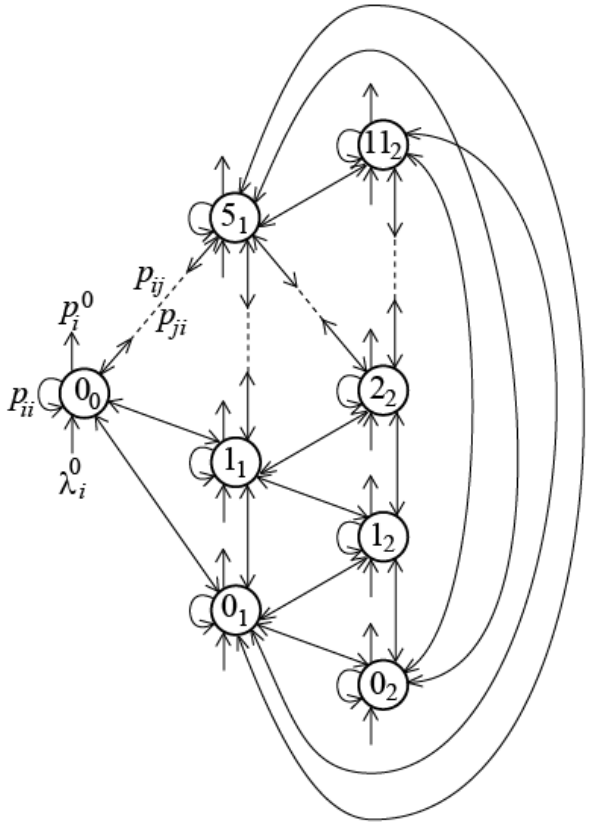


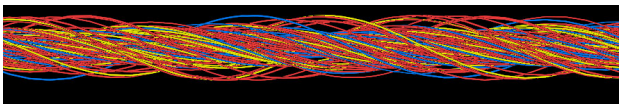
Fig. 9. Queuing system model for a yarn with three zones

This model of yarn structure is the most general and thus can be applied to the simulation of many different types of yarn including ring and open-end-spun, produced from different types of fibre; yarn can be of solid shade or made from melange blends.

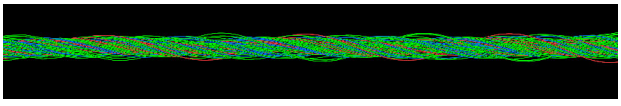
5.4 Model Implementation

The model of yarn structure described in sections 5.2 and 5.3 was implemented as an independent module of the advanced version of the YarnCAD system. This module enables the 3D images of staple fibre yarns constructed from individual fibres to be accurately simulated on the computer monitor. The input parameters to the system include usual technical specifications such as yarn count, yarn twist level and direction, the number of fibre blend components, colour and percentage of each component in the blend. In addition, the system has a database of specific parameters related to the model; these include average and standard deviation of fibre length and fibre diameter, fibre packing density distribution and migration probabilities described above. The generated yarn images can be viewed at different levels of magnification and at different angles in 3D.

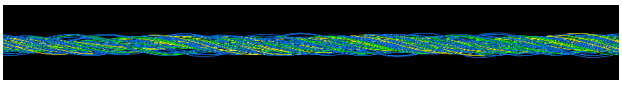
Figure 10 shows images of melange yarns of different colour composition simulated by this software. Figure 10a presents a detailed image of yarn which normally could be seen under a microscope; this image shows the complexity of the simulated structure.



a) 60% red, 20% yellow, 20% blue, magnification x10



b) 60% green, 20% red, 20% blue, magnification x5



c) 60% blue, 20% yellow, 20% green, magnification x5

Fig. 10. Computer-generated images of melange yarns

6. Conclusions

The 3D CAD simulation of textile yarns has been the work of a multi-national team of researchers in the UK for around seventeen years. The team has changed in size many times but two of the earliest members are authors of this paper. Three grants from the UK's Engineering and Physical Sciences Research Council and industrial support have sustained this project. The approach taken by the team provides true 3D yarn, fabric and garment simulations and consequently sustainable textile and garment CAD systems. In recent times the team has tackled the simulation of colour mixture/melange yarns and this has necessitated a more complicated yarn structure model based on queuing theory. The new structure model has enabled excellent colour prediction results which will soon be published and very good 3D simulations of real melange yarns. Resulting from this study new industrial interest is attracted to look at the use of dope dyed fibres as mixtures to reduce the number of stock shades required and the amount of dyeing at the more ecologically downstream materials.

7. Acknowledgements

The work reported in this paper is part of the joint research project between De Montfort University and the University of Leeds funded by the EPSRC grants GR/S77325/01 and GR/S77318/01.

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