

# A VIRTUAL PROTOTYPING TOOL FOR KNITWEAR SIMULATION

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## KEYWORDS

Knitwear simulation, virtual prototyping, continuous modelling.

## ABSTRACT

This paper both presents a 3D geometric model of knitted structures based on technical data usually used by knitted cloth experts and a physically-based model for knitwear simulation. This physically-based model relies on 3D curves modelled as successions of spline segments. It insures that at each time step the curve shape conforms to its spline definition, and thus that every property implied by the nature of the chosen spline model is verified. This fact is achieved by the animation of the spline control points. However, these control points are not considered as material points but as the degrees of freedom of the continuous object. The knitwear simulation suite encompasses topological and geometrical modelling of the rest state, mechanical modelling (including stitches bindings) suitable for our custom simulation engine based on Lagrange equations.

## INTRODUCTION

Largely widespread in the main industrial sectors, the use of software for computer-aided design (CAD) remains marginal in the textile industry. These tools are rather seldom in the “stitch field” because of the complexity of the knitting process and the computing power hitherto insufficient. This project, in collaboration with the French Textile and Apparel Institute (I.F.T.H.), follows upon the two PhD theses of J.M. Nourrit and O. Nocent which introduced algorithms and models for knitted cloth simulation, both geometrically (yarn trajectory, stitch interweaving) and mechanically (elastic behaviour, back and forth extension). This work aims at developing a software prototype for static and dynamic simulation dedicated to knitted cloth designers. This software will allow 3D modelling of knitted structures based on technical data usually used by knitted cloth experts. However, 1st of January 2005 marked the end of the ‘multifibre agreement’ of 1975, which imposed quotas to emergent countries. Chinese textile exportations towards Europe then strongly increased in the first quarter of 2005. An article of Radio France International published on internet the 25th of April 2005 announced a raise of 534 % for pullovers exportations and 183% for socks exportations. These statistics show clearly that the European knitting sector for clothing is struck hard by this competition. Thus,

the future of knitting in France could, according to our partners of the I.F.T.H, lie in technical knitting. The Textiles of Technical Use (TTU) are textile materials answering high technical and qualitative requirements (mechanical, thermal or electronic properties, durability and so on) conferring an aptitude to them to be adapted to a technical function and its environment. But the achievement of these requirements relies on an advanced technology based on a computational model of knitted structures.

## CAD FRAMEWORK FOR KNITWEAR CONCEPTION

Because of the complexity of knitted clothes, there is any complete CAD solution adapted to knitted structures at this time. The most recent works in modelling, such those of Meißner and Eberhardt (Meißner and Eberhardt 1998) for example, remain limited to knitted structures with simple topologies, and without holding account of the mechanical characteristics of the yarn, nor of the fundamental parameters of knitting (such as gauge or length of yarn absorbed by a stitch). In addition, the generated models are not three-dimensional and are used for diagrammatic representations limited to error control performed by specialists.

## Anatomy of a stitch

A stitch is subdivided into three parts: its head (upper part), legs (middle part) and feet (lower part) (Figure 1).

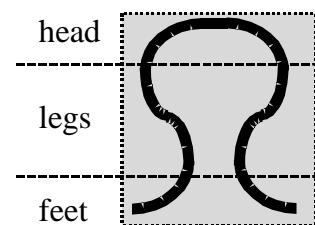


Figure 1: Stitch Parts

Since a piece of knitting is being made of intertwined stitches, one sees the face side of a stitch when its legs are visible whereas its head and feet are hidden (Figure 2a). Conversely, one sees the reverse side of a stitch when its legs are hidden whereas its head and feet are visible (Figure 2b).

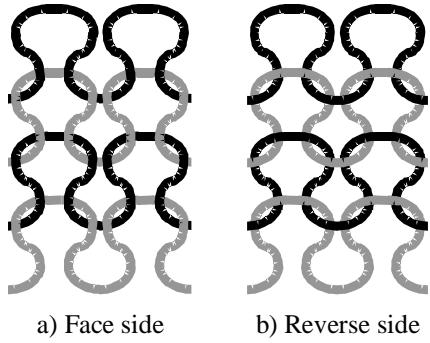


Figure 2: Basic Knitting = Plain jersey.

The most basic piece of knitting is “jersey”: the fabric is fully made of face stitches. As a consequence, one only sees face stitches whereas the other side exhibits only reverse stitches. The tuck stitches are obtained by doubling the head of the last manufactured stitch (Figure 3), thus producing the tying usually used for full cardigan rib or half cardigan rib.

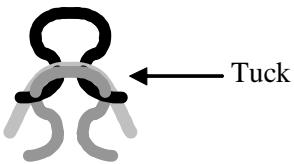


Figure 3: Formation of a Tuck

From now, we will use the term tying to mean the manufacturing process of knitting. When we mention a tying type, in addition to its name, we can use the following diagrammatic notation (standard NF G 00-025) called the “vermiculation” language by knitting professionals. It is a formalized description on point paper of the yarn as it passes around the needles. Point paper is a paper sheet covered with equidistantly spaced dots that are arranged in horizontal rows and that represent the needles.

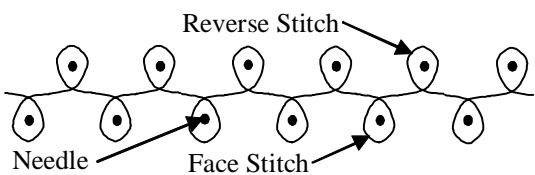


Figure 4: Graph of tying: 1 and 1 rib

Crosses indicate the inactive needles:

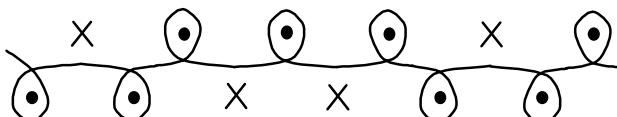


Figure 5: Graph of Tying: Derby Rib

When we do not carry out the same operations for each line of stitches, we use a graph with several lines:

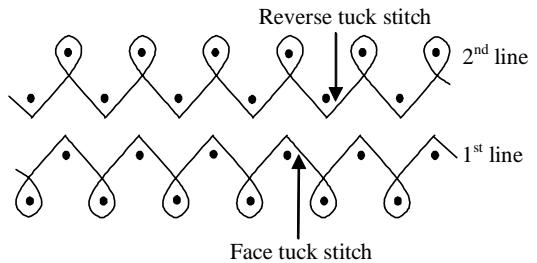


Figure 6: Graph of Tying: Full Cardigan Rib

Our geometrical model of knitted cloth relies on three-dimensional spline curves representing the trajectory of each yarn within the knitting. The 3D positions of control points of these curves are mainly defined by the tying type (way of knitting, such as for example jersey, rib, cable stitch) and by the geometrical and mechanical characteristics of used yarns. Considering the huge variety of tying and yarns employed by the stitch industry, an automatic modelling tool is necessary to avoid using static libraries of objects (too rigid and insufficient because of the large amount of tying/yarn combinations. In addition, the use of different tying within the same knitting is responsible of stitches deformations, which must be generated dynamically.

Starting from the work of Meißner et Eberhardt (Meißner and Eberhardt 1998), we carry out a 3D modelling of knitted structures application. The stitches of knitting consist of interlaced loops of yarn. According to tying considered, these loops can undergo more or less marked deformations. Initially, we build an non deformed loop, such as one can observe some in a jersey-based fabric, which is the basic tying of the knitting industry.

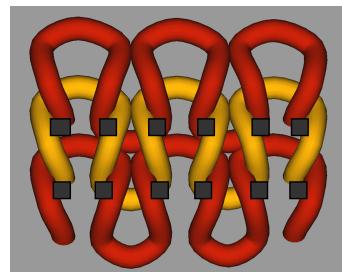


Figure 7: Bonding Points

In their article, Meißner et Eberhardt, according to confidentiality constraints due to the industrial aspect of their project, did not give much details about their work. We took as a starting point their data structures and their stitch model. On the other hand, face to the lack of precise details, we clearly did not reproduce their code and it was not our objective. Indeed, if our starting point was their article, our ambitions are different: the software developed by Meißner et Eberhardt is a 2D visualisation tool not really completely realistic on the mechanical level since it was intended for a working station. For our concern, the objective we are aiming to is to obtain a fully 3D and physically-based model. For a stitch, Meißner et Eberhardt defined 4 contact points (Bonding Point or BP). For us, when a Bonding Point is generated (Figure 7), it is associated with its relative position inside the stitch (bottom left, top left, below right or bottom right) and with the needle bed on which it was created (front

or rear needle bed). The contact points thus make it possible to define the stitches geometry.

The first stage completed, the BP are placed while holding account of the type of stitch and the neighbours or of the operation carried out (transfer to opposite needle bed or shift of a needle bed) but also of the gauge and spacing of needle beds.

The second stage consists in determining the trajectory of the wire within knitting: this operation mainly relies on the tying type (in the case of a face stitch, legs are on top whereas for a reverse stitch, the head and the feet are visible) constituting the fabric (the yarn radius is then supposed constant). We use cubic spline curves because of their simplicity of handling 3D trajectories modelling.

The principal purpose of our application is thus to reveal the knitting topology starting from yarn path notation drawn on our 3D modelling application (Figure 8).

Then we translate the drawing using an alphabet we have created. The yarn path notation (or the “vermiculation” language) is quite universal since it is mainly used by professionals of the knitting industry. This is another advantage compared to the software of Meißner et Eberhardt (even if they could undoubtedly have made this modification without too many difficulties) which received owners data. The various effects of knitting such as load, transfer and shifts of needle bed, deactivation of needles, can be generated. The alphabetical coding that we determined to translate the “vermiculation” language in a knitting definition text-based format is as follows:

|                              | «vermiculation» symbol | Associated letter |
|------------------------------|------------------------|-------------------|
| Front Side Stitch            | ○                      | g                 |
| Rear Side Stitch             | ○—○                    | e                 |
| Front Side Tuck              | ▽○                     | v                 |
| Rear Side Tuck               | ○△                     | n                 |
| Transfer to Front Needle Bed | ↓                      | T                 |
| Transfer to Rear Needle Bed  | ↑                      | t                 |
| Shift of Front Needle Bed    | → or ←                 | R                 |
| Shift of Front Needle Bed    | → or ←                 | r                 |
| Inactive Needle              | x                      | -                 |

Table 1: Our alphabet

Note: shifts of needle bed can be made on the right or on the left, that is determined by the number which follows the R or r (if the number is positive the shift is done of as many needles towards the left if not the right-hand side).

Our application provides a fully interactive framework for knitting modelling since it allows realtime 3D navigation to relocate the knitting and to turn around. In addition, if one changes the content of the text file, the digital knitting is updated immediatly.

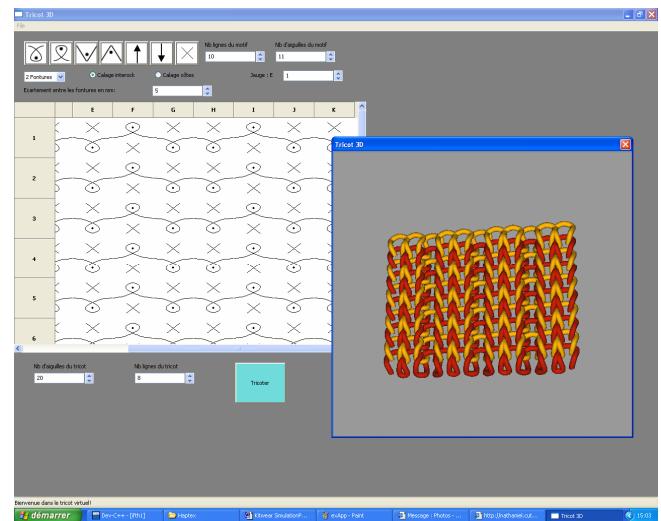


Figure 8: Our 3D Modelling Application.

Here is an example of a 3D digital 2x2 rib built from the sequence below:

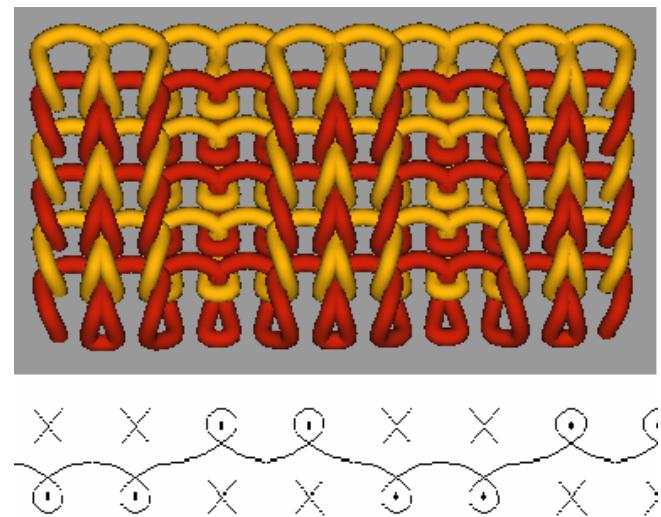


Figure 9: 2x2 Rib

## PHYSICALLY-BASED MODELLING FOR KNITWEAR SIMULATION

As cloth simulation is such an important matter, numerous solutions have been proposed. More precisely, numerous solutions have been proposed in the case of woven cloth (Terzopoulos and Fleischer 1988, Breen et al 1994, Eberhardt et al 1996, Volino and Thalmann 2000), but, not surprisingly, very few deal with the case of knitwear simulation. The fact that knitted cloth study is still marginal can easily be explained by the complexity of the knitted cloth structure of which the stitches fitting plays an important part in the global dynamic behaviour. This reflection got us to develop a model for knitwear at the mesoscopic scale, meaning fibre scale (the mesoscopic scale consists of an intermediary scale between macroscopic and microscopic scales). This choice seems to be justified and above all necessary. One could mention a similar work of Eberhardt (Meißner and Eberhardt 1998) which introduces a

topological knitwear modelling tool more than an actual knitwear simulation platform. A more recent paper of Chen et al. (Chen et al 2003) presents a knitwear model that relies on a skeleton surface made of masses and springs. Using appropriate energy functions, the model can be animated using the basic laws of dynamics. But, as the authors confess, this kind of modelling is not able to simulate the motion of cloth inferred by the yarns and their stitches. Our knitwear model is respectful of the intrinsic yarn properties (mass repartition and elasticity) and is the only one able to take into account the stitches structural complexity.

Since knitwear simulation must then rely on yarns and stitches modelling to ensure sufficient realism, yarn mechanical modelling must encompass deformable geometry, mass repartition along this geometry and internal strains. Then stitches modelling can be achieved with geometric constraints and/or external strains imposed on the yarns.

## Yarn modelling

The main geometric feature of the yarn lies in its global shape defined by a three dimensional curve called its axis. Three dimensional parametric curves are important topics in Computer Graphics and Computer Aided Geometric Design (see (Watt 1989, Farin 1990) for example) as they can be used to model manufactured objects such as ropes, threads, thin bars and so on. Among these, curves called “splines” defined as parametric functional combinations of 3D control points encounter a real success in the Computer Graphics community for their modelling facilities. Their most interesting properties in the scope of yarn axis modelling are smoothness control, realistic shapes, and, most of all, limited number of control points. This finite and limited number of control points infers a related finite and limited number of degrees of freedom (DoF) for the axis shape. This finite number of DoFs is necessary in order to achieve a numerical animation.

At this stage yarns are curves whose shapes are both realistic and suitable to numerical animation. To achieve mechanical modelling, one has to model mass repartition over the shape and internal strains, leading to the “Dynamic Material Spline” entity (Remion et al 2000, 2001), also called DMS. We then recall the main features of our DMS model.

Numerous spline models have been proposed. This diversity of the existing models eggs us on rendering our DMS “generic” to encompass as many existing spline models as possible. In this scope, the diverse models of either family may be perceived as successions of one or more curves (which we call “spline segments”) defined as parametric functional combinations with a set of blending functions  $b_i^j(s)$  of a common set of 3D moving control points  $\mathbf{q}_i(t)$ .

The time dependent position of a point on such a curve depends on its segment number  $j$  and its parametric position on this segment  $s \in [0,1]$ . The position  $\mathbf{p}_j(s,t)$  is then given by the following equation:

$$\mathbf{p}_j(s,t) = \sum_{i=1}^n b_i^j(s) \mathbf{q}_i(t) \quad (1)$$

As previously noted, dynamic animation of a spline-like object should preserve its geometrical properties over time. One simple method then consists in animating the control points of the parametric curves.

This can be achieved with dynamic animation of material control points. But we believe that the concentration of the object mass on a discrete set of 3D points is unrealistic and even more so if one remembers that some of these control points could not lie on the object for approximating spline curves.

Hence, we propose another method somehow similar in its assumptions to the D-NURBS proposed by D. Terzopoulos and H. Qin in (Qin and Terzopoulos 1996). These assumptions consist in considering the control points as the degrees of freedom of the non-discrete (say “continuous”) object. As mass repartition remains continuous, these methods are more accurate than the more straightforward animation of a set of material control points.

In the particular case of spline like objects we consider that thickness is negligible and, so, model mass repartition as  $ns$  mass density functions (one per spline segment):

These mass density functions should not be considered as giving mass density per unit length but rather per unit parametric variation of  $s$ . Hence the mass of a small part  $ds$  at point  $s$  in segment number  $j$  is  $\mu_j(s,t) \cdot ds$  (Figure 10).

$$\begin{aligned} \mu_j : [0,1] \times \mathbb{R} &\rightarrow \mathbb{R} \\ (s,t) &\mapsto \mu_j(s,t) \end{aligned} \quad (2)$$

As spline segment lengths can evolve in time, this implies that mass density per unit length can evolve too, even if  $\mu_j(s,t)$  is actually invariant in time (this time invariance simply meaning that matter is not gliding along the curve and is tied to its parametric position  $s$ ).

But in (Nocent and Remion 2001), we propose a more ‘user-friendly’ definition of mass repartition based on a per unit length density  $\rho_j(s,t)$ . These two density functions can be related according to the current DMS arc length  $l_j(s,t)$  defined as:

$$l_j(s,t) = \int_0^s \left\| \frac{\partial \mathbf{p}_j}{\partial s}(u,t) \right\| du \quad (3)$$

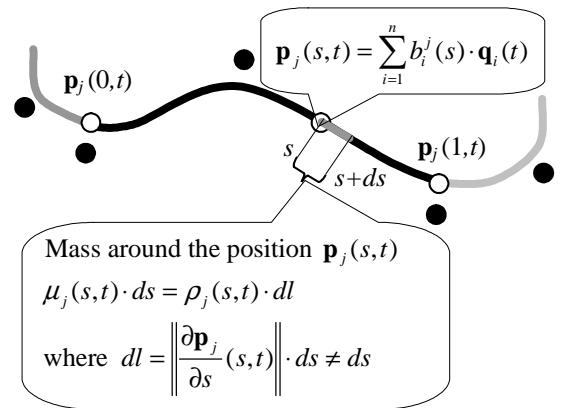


Figure 10: Mass Repartition for DMS.

Initially, we used non linear elongation springs between consecutive control points in order to simulate internal strain (Figure 11). Since (Nocent and Remion 2001), we are now able to deal with a continuous energy of deformation based on the theory of elasticity for finite displacements. This expression is fully compatible with our DMS model, much more realistic and also numerically efficient.

The physically based model finally achieved; we now have to choose the dynamic equations most suited to its nature. Since it is continuous and non-rigid with a finite number of degrees of freedom ( $3n$ ), analytic mechanics seem best suited than Euler or Newton/Euler formalisms dealing respectively with material points and solids. We therefore choose to use Lagrange equations:

$$\frac{d}{dt} \frac{\partial K}{\partial \dot{q}_i^\alpha} - \frac{\partial K}{\partial q_i^\alpha} = Q_i^\alpha \quad (4)$$

$$\forall i \in [0, n[, \alpha \in \{x, y, z\}$$

where  $K$  is the kinetic energy function,  $q_i^\alpha(t)$  are the scalar degrees of freedom and  $Q_i^\alpha$  is the power rating of the external forces in the virtual movement instilled by  $q_i^\alpha$ .

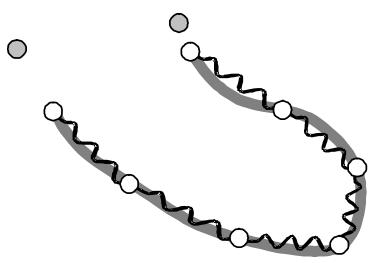


Figure 11: Elongation Springs.

In the peculiar case of DMS, Lagrange equations then yield to the following linear equations system of the unknowns  $\ddot{q}_i(t)$ :

$$M \ddot{q}^\alpha = Q^\alpha \quad \forall \alpha \in \{x, y, z\}$$

$$\text{where } M_{il} = \sum_{j=1}^{ns} \int_0^1 \rho_j(s) b_l^j(s) b_i^j(s) ds \quad (5)$$

The temporal integration of this system is a classical mathematical problem, for which a set of well-known solutions exists (Press et al 1992).

## Knitwear modelling

Obviously the knitwear model conforms to the ideas developed in the introduction. Thus, a piece of knitwear is modelled as series of yarns. Each yarn is defined by a DMS featuring its axis and further data featuring threads properties. We choose to use Catmull-Rom splines that are cubic interpolating curves. We use an enhanced version of these curves where a tension parameter has been added to the equation (Vince 1992).

In the case of yarn-based knitwear simulation, the question of initializing position or shape isn't trivial. These "initial

yarns" should be suitably intertwined to form the right stitches. In fact one has to build a topologically accurate and geometrically acceptable series of shapes, one for each yarn. Ideally these initial shapes should be mechanically refined to enhance their geometrical accuracy under the initial strains. In fact, this initially constrained state could be obtained after a few step of dynamic animation starting from repose. We thus chose, for the moment, to initialize in this repose state. The topologically accurate and geometrically acceptable initialization is obtained by rough observation of the basic knitwear feature: a jersey stitch.

If one examines the projection of a jersey piece of knitting on a plane parallel to the cloth, some interesting properties of the stitches appear, which can also be seen on Figure 12. Segments between points 3 and 5 are symmetrical from point 3 to the segments between points 1 and 3. These two points correspond to the bonding points generated by our CAD tool described above. Moreover, the stitch presents an axial symmetry.

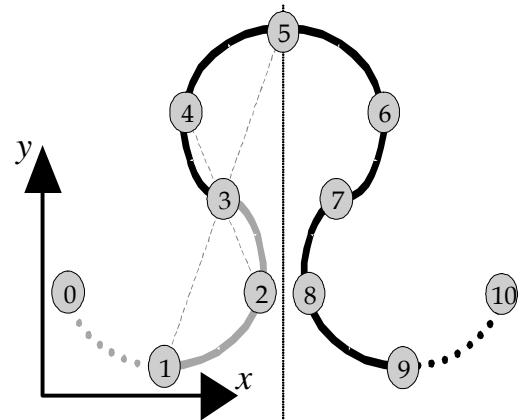


Figure 12: Stitch Symmetries.

So, we only have to build the planar geometry for spline segments between points 1 and 3 to obtain the entire stitch planar geometry thanks to those symmetries. The control points positions are determined as a function of the yarn thickness and the stitch density.

As shown in Figure 12, a stitch is made of 8 Catmull-Rom spline segments controlled by 11 points. Such a stitch is only part of a yarn, and is adjacent to up two other stitches along its yarn. Obviously these adjacent stitches will share some of its control points, namely points numbered 0, 1, 2 for the preceding one and points 8, 9, 10 for the following one. In order to simplify, yarn warping from row to row is forgotten and each row of  $N$  stitches is modelled as a dedicated yarn composed by  $8N$  spline segments for a grand total of  $8N+3$  control points.

Rows intertwining is then obtained by a convenient distribution of the elevations of control points along the third dimension (Figure 13).

At this stage we have modelled knitwear as series of yarns (one for each row) with convenient initial shapes and intrinsic mechanical properties. Our model still lacks the most significant feature of knitwear overall cohesion: the stitches bindings. These bindings are dealt with according to their implied yarns contacts.

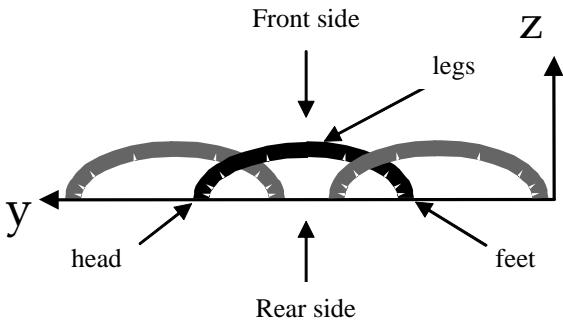


Figure 13: Stitches intertwining (yOz projection).

Contacts simulation uses jointly :

- Holonomic constraints aiming at preserving the barycentrical coordinates of points  $B_1$  and  $B_2$  in, respectively,  $(A_2B_2C_2)$  and  $(A_1B_1C_1)$  (Figure 14).
- Bi-directional springs set as in Figure 14, preventing the yarns from interpenetrating each other, and thus preserving the yarns relative orientation:

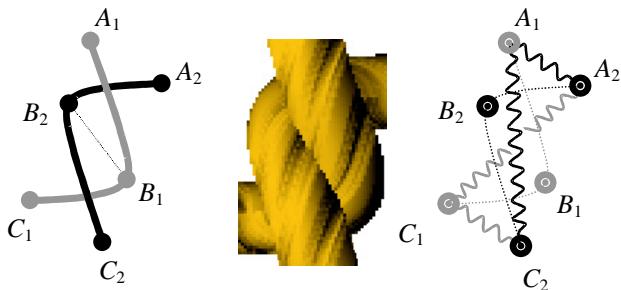


Figure 14: Barycentrical Constraints and Orientation Springs.

We know that this way of modelling contact between yarns is not general enough especially in the case of stitches load. Remion introduced the concept of ‘free variable constraints’ which is an elegant way to formulate complex constraints equations. This theoretical framework was successfully used by Lenoir in (Lenoir et al 2004) to integrate sliding contact constraints in a surgery simulation. In a near future, we want to use this kind of constraints for stitches bindings.

## CONCLUSION

In this paper, we first presented a CAD framework for knitwear conception based on an industrial standard. This tool allows creating any kind of knitwear pattern using a normalized technical language called the “vermiculation” language. A 3D visualization tool is also provided to see and modify the knitwear structure in real-time.

In the second part, we reminded the different steps of the creation of a physically-based model for knitwear from yarn modelling to stitches bindings. This mechanical model is already functional but only for a single knitwear pattern: the jersey pattern.

In a near future, we aim to merge these two independent modules in order to achieve a complete virtual prototyping

tool relying on technical data and able to simulate the mechanical behaviour of virtual knitwear patterns.

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