Yarn-Level Modeling of Non-Uniform Knitted Fabric for Digital Analysis of Textile Characteristics

From a bitmap to the yarn-level model

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Modern CNC weft knitting machines are capable to produce textiles with complex non-uniform structures and shapes in a single operation with minimum human intervention. The type of knit structure and the settings of the knitting machine significantly influence the fabric characteristics and its role in architectural comfort. However, there is still no open-access tool for fast and efficient analysis of textiles with consideration of their knit structure, especially if they are knitted non-uniformly. Moreover, the existing methodologies of digital modeling of the knit structure are not linked to the actual production of textiles on flat-bed knitting machines. This paper presents a tool that ``reads'' a bitmap image that can be as well imported into a knitting machine software and generates a yarn-level geometry of the knitted textiles, that can be further integrated into the behavior analysis software within the rhino-grasshopper environment. This methodology helps to preview and analyze knitted textiles before production and can help to optimize the programming of bespoke knitted textiles for large-scale architectural applications.

Keywords: *knitting, computational knitting, digital simulation, textile characteristics, textiles for architecture*

INTRODUCTION

Textiles are widely used in architecture both for interior and exterior applications. They are used in active-bending, air-supported structures, recently they were proven to be as well a feasible solution for the creation of resource-efficient formwork (Brennan Ba et al., 2013) and for complex bespoke concrete geometries (Popescu et al., 2018). Besides exterior applications, textiles are widely used in interior design. The use of fabrics in the interior space influences its acoustics, creates solar screens and light reflectors, helps to define a space, and increases the comfort level.

Textile environments should satisfy the aspects of safety and architectural comfort. Both can be controlled on the levels of fiber composition and the way of textile production (Anishchenko, 2020). The look and characteristics of the textiles depend on their structure and choice of yarns. On the level of fiber engineering, there is constant research of resistance to fire, ultraviolet rays, moisture, and other aspects that should be considered for construction. The way of fabric production, density, and thickness of the material play as well a significant role in the perception of architectural textiles and their role in architectural comfort. All these characteristics influence the way we perceive the fabrics and their capacity to distribute light and air, their insulation characteristics, and structural resistance.

Knitted textiles in large-scale applications are mostly used in the same way as woven materials and in most cases, their complete potential is not revealed. The main benefit of the knitted textiles with respect to woven ones is the possibility to create a non-uniform composition and complex shapes minimizing the need for cutting and connecting separate pieces. Moreover, the knitted textiles are naturally much more flexible and elastic because their structure benefits easy elongation without the deformation of fibers (Cooke, 2011). It increases the lifespan and the recovery properties of a material.

Knitting has advantages at the production stage due to the possibility to program every single loop of textile individually, respecting the limitations of a knitting machine. It enables a high variety of patterns and yarns composition to be combined in a single piece of fabric, to obtain an optimized bespoke fabric structure. The requirements to the particular areas of a piece of textile can be defined on the design stage, for example, to detect where an open structure is needed to provide more natural light, or more dense and bulky to absorb sound. However, there is no actual link between the analysis of required characteristics and the production of the textiles. As well there is no open-access database of textile structures that could help to choose an optimal knit pattern and especially combine different ones together.

The software for the CNC-knitting machines is relatively easy to use to design and produce flat uniform textiles. Production of more complicated structures with a specific shape or with non-uniform compositions requires a lot more experience. Moreover, it is generally impossible to preview the complex structures within the software. The built-in visualization system within some knitting machine software, for example, M1Plus by Stoll, renders well simple two-dimensional patterns but fails to render more complicated structures and shapes. The topic of rendering and predicting the behavior of knitted fabrics is under the research for animation design. Though there is ongoing research that explains the physics of the knitted textiles, there is no actual way to link the digital simulation to the actual production and to predict the physical characteristics of textiles.

The methodology described in this paper aims to facilitate the preview and production of bespoke knitted textiles. In the further chapters is presented a script based on Rhinoceros-Grasshopper-Python environment that creates a lightweight three-dimensional model of a knit structure taking as an input a bitmap image that can be as well used to produce textile on a knitting machine. The main aim of this tool is to create a direct link between real textile production on flatbed knitting machines and its simulation in the digital environment. As an output, the script generates geometry representing the knitted textile depending on the user request: points, lines, curves, or surfaces for further integration of the model into the existing behavior simulation plug-ins.

The suggested tool is designed as a first step of the methodology of automatic generation of the code for the knitting machines for the production of bespoke non-uniform performative fabrics. This research aim is to facilitate the overall process of the design of textiles from the choice of optimal textile structure to real production.

STATE OF THE ART

Knitting in general is a widely researched field. But being mostly used in the fashion industry, where the production tips are normally kept in secret, this research doesn't get much spread in the open-access networks (Underwood, 2009). In recent years knitting has attracted the attention of people from different fields: product design, aerospace, automotive, marine, geotextiles, medicine, protective clothing industries. Moreover, there is an interest in knitting from the computer animation field to digitalize the behavior of knitted textiles. The use of knitting in architecture is a relatively new topic. Among the innovative applications of the knitted textiles are stay-in-place concrete formworks (Popescu et al., 2018), knitted textiles with non-homogeneous structures for the bending-active structures (Deleuran et al., 2015), integration of conductive fibers into the knitted textiles for the interactive environments (Ahlquist, 2016).

The State-of-the-Art relative to this paper can be divided into 3 major categories: production of non-uniform knitted fabrics, digital analysis of knitted textile on a macro mesh level, and digital analysis on micro yarn contact level.

Knitting of non-uniform textiles is quickly getting popularity within the fashion field, especially by sports brands for the production of garments and shoes to engineer zones for temperature regulation, sweat, movement, support, etc. The choice of a fabric structure is based on physical tests and the experience of knitting engineers. Programming and knitting three-dimensionally shaped seamless non-uniform garments still require more time in respect to the production of uniform flat fabric. This time is not always compensated by the reduction of the number of operations of cutting and sewing, thus the seamless production is not necessarily economically valuable. It may be different for the production of large-scale bespoke textiles for architectural applications, where each programmed piece should be produced only once or in a very limited amount of copies and each additional prototype may increase significantly the costs. Thus, large-scale bespoke applications require more precise programming and simulations to avoid the trial-and-error method and wasteful full-scale prototyping stage.

Normally to analyse fabric on a macro level a piece of textile is presented as a mesh in which all the edges are springs that tend to contract. This gives a relatively realistic image of the tensile behaviour on a large scale. This way it is possible to see in a fast manner the behaviour of a textile piece but without consideration of its structure and the behaviour on a yarn level.

Tamke et al. (2016) have proposed a methodology of import of bitmap images with predefined shape and structure divided into zones depending on structural requirements in the knitting machine code. The projects of Hybrid Tower and Isotropia canopy (Thomsen et al., 2019) for Biennale 2018 use bespoke CNC-knitted textiles with complex structures. Working with bending-active systems, they perform as well the analysis of the textiles on macro-scale within the rhino-grasshopper environment, using software like Kangaroo, Kiwi3D, SOFiSTiK ((La Magna et al., 2018)). They detect the areas with different structural requirements and export the data as a bitmap for direct import in the knitting machine software. The choice of the most suitable knit pattern is done through a series of physical experiments including 3d scanning.

A research group from CIRTex college from Shenkar in Israel (Karmon et al., 2018) works on automatization of the creation of knitted patterns based on the prediction of fabric deformation which helps to achieve more precision between design and production stages. It is done on a mesh level by defining various elasticity characteristics to areas of fabric with different knit patterns.

The modeling of knitted textiles on the yarn level is mostly researched for animation purposes, where it is important to obtain a realistic image, but not unveil the performative characteristics of the fabric. In 2008 Kaldor et al. have suggested an efficient methodology of analyzing the knitted textiles on yarn level considering yarn-yarn friction and sliding, pulls, frayed edges, or detailed fracture between all the points in the model, which creates a reliable, but however very heavy computational model. Yuksel et al. (2012) suggested a 'stitch mesh' methodology with a finer mesh representing the layout of stitches in the garment. It helped to significantly decrease the time of calculations.

Cirio et al., (2014, 2017) propose an efficient representation of loops geometry and kinematics, capturing the essential deformation modes. The design force models reproduce macroscopic characteristics of knitted fabrics. McKee et al., 2017 and Liu et al., 2018 use finite element analysis to check the behavior of textiles on a yarn-level scale. Sperl et al. (2020) have proposed a method of animating yarn-level cloth effects using a thin-shell solver. They use a large number of yarn-level simulations to build a model of the potential energy density of the cloth and then use this energy density function to compute forces in a thin shell simulator.

While the macro-scale simulation observes the overall behavior of fabrics without consideration of fabric structure, the micro-scale yarn-level contacts analysis provides a way more realistic model, though with much higher requirements for the time of calculation and the computational capacities of a machine. Thus, the existing methodologies of modeling knitted textiles are not suitable for analyses of textiles on a large scale with consideration of the textile structure. As well, the current yarn-level simulations are not linked to the real production of knitted textiles and to physical simulation analysis software.

METHODOLOGY

The aim of this research is to create a methodology of digitalizing the knitting texture on yarn-level in a fast and computationally light manner using the logic of a CNC-knitting machine for further integration in performance analysis software.

This paper suggests a methodology of modeling the knitted textiles following the operational logic of a knitting machine to obtain the connection between the digitalization and actual production of textiles. This allows to facilitate the preview of the final result and to use the resulted three-dimensional model for further analysis. However, the paper doesn't specify the compatibility of the model with some particular plug-ins for physical analysis. Instead, it suggests a tool that can generate as an output various types of geometries from points to surfaces that would represent the required knit structure.

To enable yarn-level modeling of non-uniform knit structures it is important to understand how a knitting machine works. Initially designed to create plain fabrics, the interface of a knitting software reminds a raster 2D graphic editor where every "pixel" contains instructions about which actions should perform each pair of needles located on the parallel beds. These instructions can be given manually by designing directly inside the knitting machine software, otherwise, they can be also imported as a bitmap. During the import, it is possible to choose manually the correspondence between each color of the image to the commands of the software or upload the saved settings which will automatically assign the predefined commands to each color.

The following chapters explain the basic principles of the work of a knitting machine and suggest a script that is repeating in a simplified manner the needle actions in a digital environment. As an input, it takes a bitmap image where each color corresponds to a set of instructions. In the further stages, the resulted geometry is integrated into the Kangaroo2 plug-in for the application of the forces to see the behavior of the fabric. The same model can be as well integrated into other plugins for further physical analysis within the grasshopper environment.

WORKING PRINCIPLE OF A WEFT KNITTING MACHINE

The modern knitting machines consist of 2 needle beds - two parallel platforms on which are located the hook needles (Figure 1). The distance between them is set by the gauge of the machine and influences the space between the loops and their size. The needles on different beds are located perpendicular to each other permitting the transfer of loops from one side to another. Items located on opposite beds in front of each other will be further called "corresponding needles" or "needle pairs". The beds can move horizontally relative to each other to change the position of the needles on different beds respectively.

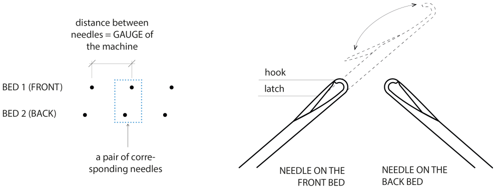


Figure 1
On the left: a representation scheme of 2 needle beds. On the right: graphical scheme of the needles

Any manipulation with needles and yarn is called a stitch. Any movement of exiting stitch to another needle - a transfer. Simple knitting patterns can be done with the use of one needle bed. The second bed serves to create more complicated patterns that would include the use of both beds in parallel and the transfer of the loops from one needle to another.

There are 3 basic operations with yarn that each needle can do: loop, tuck, or float. The essential base for all the patterns is a loop or a plain stitch. A new loop is formed when a yarn is drawn through a previously existing loop. Alternative stitches are tuck and float. For the tuck stitch, the needle creates a new loop but does not draw it through the previously existing one: it keeps both stitches on the same needle. The tuck can be also done on an empty needle. For the float, the loop is skipped, and the needle keeps the previous loop.

All these operations can be done both on front and back needle beds. In a knitting machine code, the operations that each needle needs to perform are described consistently. By default, the carriage starts moving from the right side of the needle bed and the direction alternates every row. During every single run in one direction, the carriage does needle actions with yarn or actions without yarn - transfers. Operations with transfers always require more time since the carriage should pass at least 2 times. Within one pair of corresponding needles, the needle actions can be performed consequently on both needles in one single carriage run if they use the same yarn, or separately in two or more runs if the yarns are different or special instructions were given. The order of these actions is defined for each pair of needles.

Transfer means moving an existing loop from one needle to another. It can be done only between the corresponding needles of opposite beds. To do that an empty needle from one bed passes through a loop on a corresponding needle of another bed to pick it up. During one carriage move, the transfer can be done only in one direction (for instance from front to back). Thus, for the rows where are present transfers in both directions, the carriage should do 2 passes. In case if the transfer should be done between two needles of the same needle bed, the loop should be first transferred to the opposite bed and then be transferred back to the original one after the rack was moved.

DIGITAL MODELING OF KNITTED TEXTILES

The script to digitalize the structure of knitted textile on the yarn level is programmed within the Grasshopper for Rhinoceros and consists of three major parts: Reading of a bitmap, generation of loops geometry, and application of forces. Following the logic of the knitting machine that was described above, the suggested script requires as input two sets of data: a bitmap image, in which every pixel corresponds to the needle actions on one needle pair, and a table of correspondence where are described the commands that should be performed for each "pixel" depending on its color.

Reading the bitmap

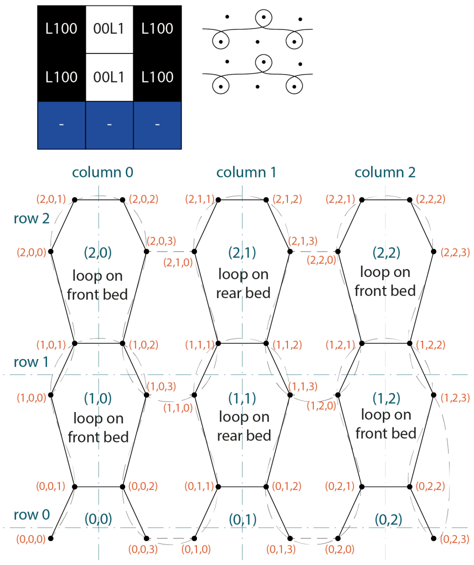
At the first stage, the image, imported as a bitmap file, is read by the Aviary1 plug-in for Grasshopper that works with raster images. This script extracts the width and the height of the image, and the RGB color of each pixel. In the next step, the Python script confronts the data from each pixel of the image to the data in an imported table, where each RGB is transformed into a special code described below and the meanings are stored in a "matrix". Matrix is a grafted list, that contains a series of sub-lists corresponding to the rows from the bottom to the top of the bitmap, which contain the codes with the needle actions.

The nine-digit code assigned to each pixel has its own meaning and corresponds to the needle actions that should be performed to the current needle pair. The first two digits represent the needle actions with yarn on the front bed. The first digit, which can be L, T, or F corresponds to “loop”, “tuck”, or “float” respectively. 0 instead means that no action should be performed. The second digit says which yarn should be used for this operation. The next couple of digits has the same meaning but corresponds to the actions on the back bed. The last 5 digits correspond to the transfer operations. The 5th digit may have meanings 0, F, or B (no transfer, transfer to the front, transfer to the back). The last 2 pairs instead inform if the front or rear racks should be moved to a side, moving the loops to the neighboring needles.

Generation of the loops geometry

The second part of the script generates the geometry of the stitches. As an input, it takes the “matrix” with a code for each stitch, and the initial positions of the needle beds in respect to each other. As an output, the script generates four types of geometry: points, lines approximating the segments of the yarn, splines, and pipe surfaces. Generation of the pipe surface takes a significant part of the time of calculation of the script and can significantly slow down the overall process for calculation of large pieces of fabric. For this reason, the output can be limited to the generation of points and lines to speed up the calculation process.

As a base for the knit geometry is used a hexagonal grid as suggested in (Cirio et al. 2017). The hexagonal grid allows to represent in a simplified way the geometry of loops and keep all the points of the hexagons as the nodes. To represent the two beds of a knitting machine, two parallel grids of the same size are generated. They can be moved with respect to each other. All the points of both grids are divided in a three levels tree structure corresponding to the row, the column numbers, and the point index inside of the hexagon. The sizes of the grids depend on the size of the bitmap (Figure 2).



L100	00L1	L100
L100	00L1	L100
-	-	-

Figure 2
Transformation of a part of the input matrix to the hexagonal grid, where each node has a code corresponding to three-level data tree and each hexagon has a type code

Depending on the number of yarns introduced in the matrix, the script creates one or more lists which, contain consequent sub-lists of the points that yarn is passing to form stitches. Each sub-list contains several points corresponding to the type of the stitch: 8 points for loop, 4 points for tuck, and 2 for float (Figure 3).

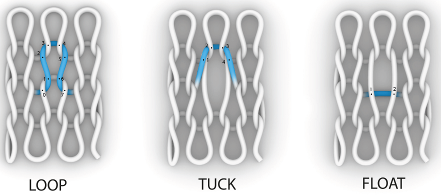


Figure 3
Loop, tuck and float stitches generated on the front bed

After each stitch, the lists representing the occupancy of each needle are updated, saving information about how many loops are contained by each needle. The loop erases all the previous information

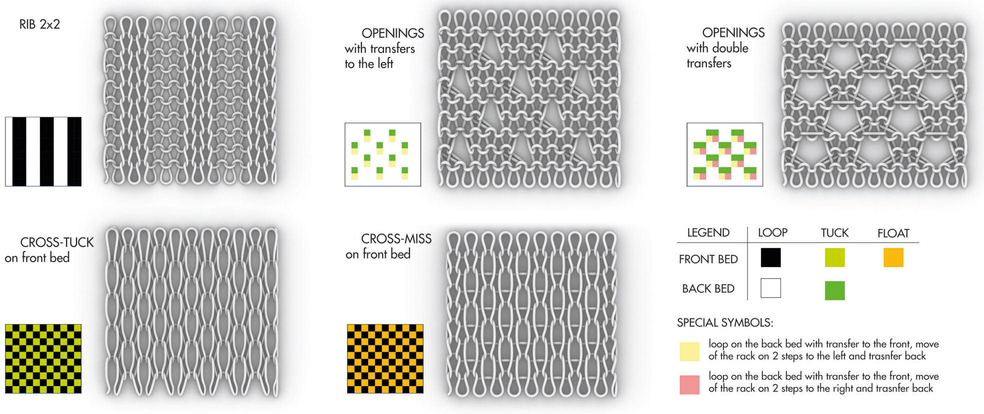


Figure 4
Various knit structures knitted with one yarn. on the left of each pattern is the bitmap imported as input and on the right is the output mesh

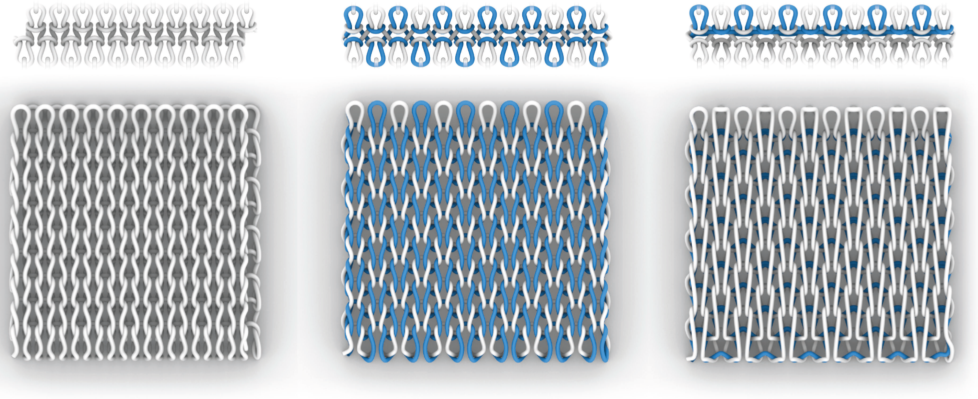


Figure 5
From the left to the right: double jersey knitted with one yarn with the back rack moved on half a gauge to the right; interlock fabric knitted with two yarns; interlock with alternating loops and floats knitted with two yarns

and sets the occupancy to 1. The tuck stitch adds an additional loop, keeping the previous ones and the float doesn't change the number of loops on the needle, so the previous number remains. This information is updated as well after the transfers. Before each float or tuck, the script is also checking if there are any loops on the needle and if yes, elongates them, moving the points to the next row.

As a result, the script generates one or several lists of points corresponding to the number of yarns used in the code. After the end of the calculation, single continuous curves or pipe surfaces representing the yarns are generated. The thickness of the pipe surface may be modified to represent different types of yarns. Figure 4 shows various knit structures with 1 yarn generated with the described script. It includes textile structures knitted on one and two needle beds, some of them with the use of transfers. Figure 5 demonstrates patterns knitted on both beds with the use of all of the needles with one and two yarns.

With the increase in the size of the textile, the computational effort obviously grows. Since the script is calculating the positions of points that form the yarn shape one after another independently, the change of time to calculate the position of points and preview the springs or spline is relatively linear with respect to the number of loops. Instead, the calculation effort to preview the pipe surface grows significantly with the increase in complexity and fails when the fabric is too big. The graph in figure 6 demonstrates the almost linear dependency of the time in seconds needed for the calculation of the number of loops in the fabric.

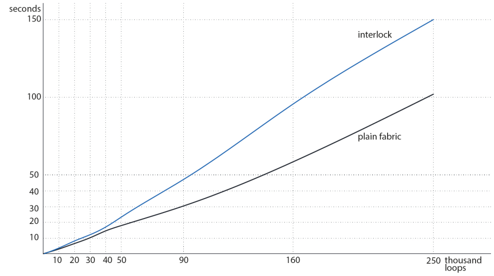


Figure 6
The graph demonstrating the dependency of time in seconds needed for the calculation depending on the number of loops.

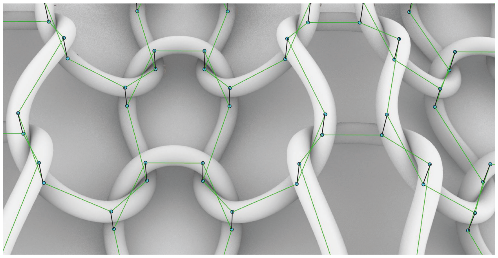


Figure 7
Green lines connect the continuous list of points that approximate the pieces of yarn. Black lines connect the corresponding points at the nodes

At the stage of loops modeling the script produces well recognizable knit structures, which can be already used to preview an approximate look of the textile before the production. However, since the physical forces acting both internally and externally are not considered yet, the further step of the calculations is required to obtain a more realistic model.

Application of forces

The application of forces is done through the Kangaroo2 plug-in for Grasshopper. To launch the simulation the collection of points and two sets of lines connecting them are required as input. The first are the lines that connect the neighboring points in the flattened list of points produced by the loop generation script and the second are the lines connecting the corresponding points (Figure 7).

The first group of lines represents the pieces of yarns that should maintain their length. Though in reality, it is not a line, but a curve segment that should keep the original length, inserting the lines in the calculation as springs provides a big economy in time. The yarn within the knit structure tends to straighten and obtain the initial shape, so the neighboring segments of the yarn tend to maintain an angle of 180 degrees between each other.

The second set of lines represents the contact points of the yarn. These lines should maintain the minimum length equal to a double radius of the yarn and stay perpendicular to the plane of the local area of fabric. For the current experiment, to see how the textile will behave in a relaxed horizontal position thus aligning the springs to the axis z. To switch to the simulation of knitted fabric placed in a not horizontal position, it is necessary to instead set an angle between the connection points and the plane of the nearby loops close to perpendicular.

To simulate gravity, the Kangaroo2 gives a minimum weight to all the points of the lines to keep the internal forces dominant with respect to the gravity force. The anchors are set to all the points located on the border of the piece to see the behavior of a slightly stretched fabric.

The current script still needs to be calibrated to achieve precision with the use of different yarns. However, the deformation of the fabrics after the application of forces demonstrates quite reliable results. For example, plain fabrics tend to deform the stitches in a diagonal direction; in cross-miss fabrics, the loops tend to become more round to occupy all the available space while the yarn tends to straighten. The analysis performed with Kangaroo demonstrates very similar behaviour to the plain and cross-miss fabric knitted with a hairy Polyester fibre

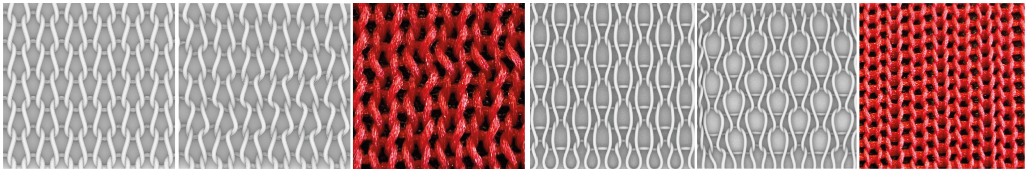


Figure 8
From the left to the right: single jersey before the deformation; single jersey after deformation; the picture of a physically produced sample. Cross-miss before the deformation; cross-miss after deformation; the picture of a physically produced sample

which slows down the sliding effect (Figure 8).

Since the yarn is approximated with springs and points, the simulation of the fabric behavior in the Kangaroo2 requires only slightly more computational effort to calculate additional forces with respect to the classical methodology where a mesh is represented as a rectangular grid of springs.

CONCLUSION

The methodology and script presented in this paper suggest a way of modeling a simplified knitted textiles structure produced on a CNC knitting machine. It proposes an intermediate way between the simulation of knitted fabric on mesh and yarn-contacts levels, approximating the yarn with lines to minimize the time of calculation. For this reason, it provides a less realistic model in respect to existing yarn-yarn level simulations but provides a way of representation of the fabric textile with respect to its structure for the macro-scale simulations.

One of the main advantages is that the script permits the preview of non-uniform knit patterns within the rhino-grasshopper environment and provides discretized geometry that can be directly introduced into the other plugins within the same environment for further analysis. For example, the output surface can be introduced into the Ladybug plugin to detect the light penetration characteristics, or to the Pachyderm plugin to analyze the acoustic characteristics. The reliability of this analysis is still to be performed by comparison of the computational models and the real-life physical tests.

The proposed methodology has several ways of further development. The first one is the calibration of the methodology by the series of physical experiments to detect better the forces acting internally and externally of the textiles. As well, it is important to understand the influence of the type of fibres used for the production. Understanding the influence of the fibre type is crucial for the further understanding of the fabric behaviour.

Another important aspect to develop is the possibility to generate the structure of three-dimensionally knitted textiles. The methodologies of knitting fabrics of particular shapes were carefully described by (Popescu et al., 2017) and (Hodgins et al., 2016) who have proposed converting a 3d mesh into knitting instructions. Another approach of simplifying the process of programming the 3d textiles was proposed by (Kaspar et al., 2019), who have designed an interactive system for simple garment composition and surface patterning. Within the framework suggested in this paper, the three-dimensionality can be obtained on the phase of application of physical forces by detecting the springs of the long loops that should contract.

The direction in which this current research will develop is the design of a complementary tool that will store the information obtained by physical and digital simulations of various knit patterns, save them in a database, and advise the optimal choice of the knit structure depending on the required characteristics for bespoke projects.

Digitalization and prediction of the behavior of knitted textiles have great potential for the fashion, engineering, and construction industries. However, there are still many open gaps in the field that do not reveal the complete potential of CNC knitting.

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REFERENCES

Ahlquist, S 2016, 'Sensory material architectures: Concepts and methodologies for spatial tectonics and tactile responsivity in knitted textile hybrid structures', *International Journal of Architectural Computing*, 14(1), pp. 63-82

Anishchenko, M 2020, 'Bespoke knitted textiles for large-scale architectural projects', in Paoletti, I and Nastri, M (eds) 2020, *SpringerBriefs in Applied Sciences and Technology*, Springer, pp. 75-82

Cirio, G, Lopez-Moreno, J and Otaduy, MA 2015 'Efficient simulation of knitted cloth using persistent contacts', *SCA '15 Proceedings of the 14th ACM SIGGRAPH / Eurographics Symposium on Computer Animation*, Los Angeles, California, pp. 55-61

Cirio, G, Lopez-moreno, J and Otaduy, MA 2017, 'Yarn-Level Cloth Simulation with Sliding Persistent Contacts', *IEEE Transactions on Visualization and Computer Graphics*, 23(2), pp. 1-11

Cooke, B 2011, 'The physical properties of weft knitted structures', in Au, KF (eds) 2011, *Advances in knitting technology*, Woodhead Publishing Limited

Deleuran, A, Schmeck, M, Quinn, G, Gengnagel, C, Tamke, M and Thomsen, MR 2015 'The Tower : Modelling , Analysis and Construction of Bending Active Tensile Membrane Hybrid Structures', *Proceedings of the International Association for Shell and Spatial Structures*

Hodgins, J, McCann, J, Grow, A, Albaugh, L, Mankoff, J, Matusik, W and Narayanan, V 2016, 'A compiler for 3D machine knitting', *ACM Transactions on Graphics*, 35(4), pp. 1-11

Kaldor, JM, James, DL and Marschner, S 2008, 'Simulating knitted cloth at the yarn level', *ACM Transactions on Graphics*, 27(3), p. 1

Karmon, A, Sterman, Y, Shaked, T, Nir, S and Sheffer, E 2018 'KNITIT: A Computational Tool for Design, Simulation, and Fabrication of Multiple Structured Knits', *ACM SYMPOSIUM ON COMPUTATIONAL FABRICATION*, Cambridge, MA, USA

Liu, D, Shakibajahromi, B, DIon, G, Breen, D, Kontsos, A, Seiki, S, Lab, HT, Breen, D and Kontsos, A 2018, 'Genevieve Dion A Computational Approach to Model Interfacial Effects on the Mechanical Behavior of Knitted Textiles', *Journal of Applied Mechanics, Transactions of the ASME*, 85(4), pp. 1-12

La Magna, R, Fragkia, V, Langst, P, Lienhard, J, Noel, R, Baranovskaya, Y, Tamke, M and Thomsen, MR 2018 'Isoropia : an Encompassing Approach for the Design , Analysis and Form-Finding of Bending-Active Textile Hybrids', *Proceedings of the IASS Symposium 2018 Creativity in Structural Design*, Boston, USA, pp. 1-8

McKee, PJ, Sokolow, AC, Yu, JH, Long, LL and Wetzel, ED 2017, 'Finite element simulation of ballistic impact on single jersey knit fabric', *Composite Structures*, 162, pp. 98-107

Mozafary, V, Payvandy, P and Rezaeian, M 2018, 'A novel approach for simulation of curling behavior of knitted fabric based on mass spring model', *Journal of the Textile Institute*, 109(12), pp. 1620-1641

Popescu, M, Reiter, L, Block, P, Flatt, R, Liew, A and Van Mele, T 2018, 'Building in Concrete with an Ultra-lightweight Knitted Stay-in-place Formwork: Prototype of a Concrete Shell Bridge', *Structures*, 14, pp. 322-332

Popescu, M, Rippmann, M, Van Mele, T and Block, P 2017 'Automated Generation of Knit Patterns for Non-developable Surfaces', *Design Modelling Symposium Paris 2017. Humanizing Digital Reality*, pp. 271-284

Tamke, M, Baranovskaya, Y, Deleuran, A and Monteiro, F 2016 'Bespoke Materials For Bespoke Textile Architecture', *Proceedings of the International Association for Shell and Spatial Structures*, Tokyo

Thomsen, MR, Baranovskaya, Y, Monteiro, F, Lienhard, J, La Magna, R and Tamke, M 2019 'Systems for transformative textile structures in CNC knitted fabrics – Isoropia', *Proceedings of the Tensinet Symposium 2019*, pp. 95-110

Underwood, J 2009, *The Design of 3D Shape Knitted Preforms*, Ph.D. Thesis, RMIT University

[1] https://arxiv.org/abs/1904.05681