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## 3D knitting using large circular knitting machines

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**Abstract.** For the first time 3D structures can now be produced on large circular knitting machines. Till date, such structures could only be manufactured on flat knitting machines. Since large circular knitting machines operate much faster, this development increases the overall productivity of 3D knits. It thus opens up a totally new avenue for cost reduction for applications in sportswear, upholstery, aerospace and automotive industry. The following paper presents the state of the art regarding the realisation of three dimensional fabrics. In addition, current knitting technologies regarding three dimensional formations will be explained. Results of the pretrials explaining the change in knitted fabrics' dimension, executed at the Institut für Textiltechnik of the RWTH Aachen University, will be presented. Finally, the description of the 3D knit prototype developed will be provided as a part of this paper.

### 1. Introduction

The advantage of flat-knit technology lies in its possibility of great pattern variety up to three dimensional structures. The production using flat knitting technology is limited in productivity by the discontinuous movement of the carriage and the amount of feeding systems (4-6). In comparison to flat knitting machines the productivity in terms of m<sup>2</sup>/min is higher due to the continuous movement of the needles as well as due to the higher amount of feeding systems (up to 144) (Table 1). As a result, large circular knitting machines are used for mass production in industry in order to produce T-Shirts or mattress covers. In order to realize the final product, the textile is produced as a fabric roll. The material is then cut and sewn in a downstream process in order to get the final ready-to-wear product.

Using the current state of the art technologies, three-dimensional products cannot be produced on large circular knitting machines. In this paper, the term 3D does not include seamless knitting, i.e. producing knitted tubular garments without side seams requiring only minimal sewing operation to complete the final garment. [1] This technology is commercially used for fashion application and produced by seamless machines by e.g. Santoni Srl, Brescia, Italy. [2]

Three-dimensional weft knitted fabrics can be realized by the use of flat knitting machines. 3D knitting eliminates process steps of the assembly, such as cutting and joining. 3D knitting allows the production of three-dimensional knitted fabrics in one process step on a single machine. [3]

The main advantages of 3D knitted fabrics are: [4]

- Production of complex 3D shaped knitted fabrics
- Drapability characteristics of knitted fabrics

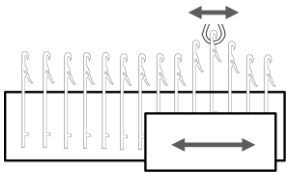
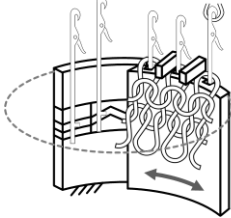
Current techniques allow the creation of three-dimensional weft knitted fabrics by:



- Combination of different mesh heights / sinker heights (flat and small circular knitting)
- Flat knitting process: Variation of the number of active needles between courses ("needle parking") in order to add loops [3,5]

The advantages of 3D knits has been an active area of research in using 3D flat knits for composite applications [4, 6, 7]

**Table 1.** Comparison of flat and large circular knitting technology [8, 9, 10, 11]

	<b>Flat knitting</b>	<b>Large circular knitting</b>
<b>Principle of needle movement</b>		
	Discontinuous needle movement	Continuous needle movement
<b>Amount of feeders</b>	< 6	44-144
<b>Needle Speed</b>	1.3 m/sec	2.2 m/sec
<b>Knit-to-wear production</b>	Final product Knit and wear	-Not possible -Designed for mass production -Fabric roll
<b>Flexibility</b>	-Machine width limits the product's width -3D structures realizable -Online decrease and increase of loops -(needle parking)	-High limitations regarding pattern & color variety -No 3D structure possible

The approach undertaken at the division of knitted fabrics at the Institut für Textiltechnik of the RWTH Aachen University, Aachen (ITA) focuses on the development of three-dimensional knits with a goal of increasing overall efficiency by exploiting the benefits of large circular knitting machines. The combination of high productivity with an increased flexibility leads to a reduction on costs in the production of final knitted products for industrial applications (sports industry, medicine, automotive, aeronautics and astronautics sectors).

The paper presents a prototype of a three dimensional knit by the use of large circular weft knitting machines (patent application). This is the first global development of such a technology which promises a substantial increase in overall efficiency for the development of 3D knitted products.

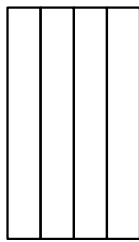
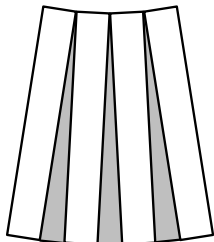
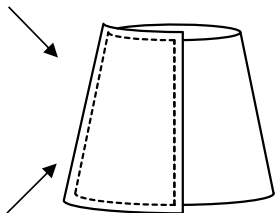
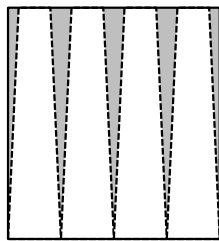
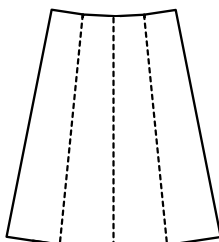

## 2. Design of sewing pattern in textiles

A three-dimensional textile structure results from joining of two-dimensional sections. These sections are shaped in their outline in such a way that the 3D model intention is realized by the combination of the cuts. [12] Cutting patterns represent the two-dimensional components of a (three-dimensional) garment. The cutting design is part of the design process and product development. The pattern is the basis for garment production. The development and dimensioning of cutting patterns for different clothing sizes, called grading, are complex tasks. The designer or cutting technician creates a three-dimensional garment made of unstable two-dimensional fabric cutouts that cannot be worn by a flexible body in its current form.

In garment manufacturing, the manual creation of cutting patterns has been replaced by available CAD based systems. Commercially, these systems are sold by Gerber Technology GmbH, Ismaning, Germany, Lectra Systems SA, Paris, France, Optitex Europe, Milano, Italien, PAD System™ International Limited, Hong Kong, China and TukaTech, Los Angeles, CA, USA. [12, 13, 14, 15]

In order to adapt a garment to the physical requirements of the 3D body, two methods are commonly used in the garment industry. These two methods are: (a) Reduction of surplus area and (b) Addition of fabric material. Reduction of material is achieved by means of darts, seams, folds or gathers. Surface addition is possible by inserting additional material. By reducing or adding material, circumferential differences, for example, between the waist region and the chest region, are compensated. In Table 2 the principle of the addition and reduction of the area using the example of a conical shell is illustrated. [14, 15, 16, 17, 18]

**Table 2.** Principle of material addition and reduction using the example of a conical shell [14]

Principle	2D fabric	Cutting pattern	3D structure (garment)
<b>3D by material addition</b>			
<b>3D by material reduction</b>			

### 3. State of the art

The technique of so-called needle parking is widespread in the production of 3D knitted fabrics on **flat knitting machines**. The technique of needle parking includes two operations of shaping:

- Extension: Increasing the number of active work needles
- Constriction: Reducing the number of active working needles

On flat knitting machines, needles can either be activated or deactivated by electronic needle selection. Both operations are performed by activating and deactivating of individual needles. While increasing or decreasing the number of active needles, some needles remain inactive for a certain time. The inactive needles hold the last knitted loop. The flat knitting take down continuously increase the tension on the stitches which are "parked" on inactive needles. The load to be applied to the yarn leads to a distortion of the loop. Exceeding the maximum tensile strength of the thread during the load application process leads to thread breakage. Using the method of needle parking for knitting three-dimensional structures, the main task is to transfer the three-dimensional shape to a two-dimensional pattern. The forming operations (increasing or decreasing the number of knitting needles) are determined by the two-dimensional pattern. [3, 4, 5, 6]

**Small circular knitting machines** have a pendulum function for the production of socks or bandages. The product width is queried on the basis of the machine size. Small circular knitting machines have a

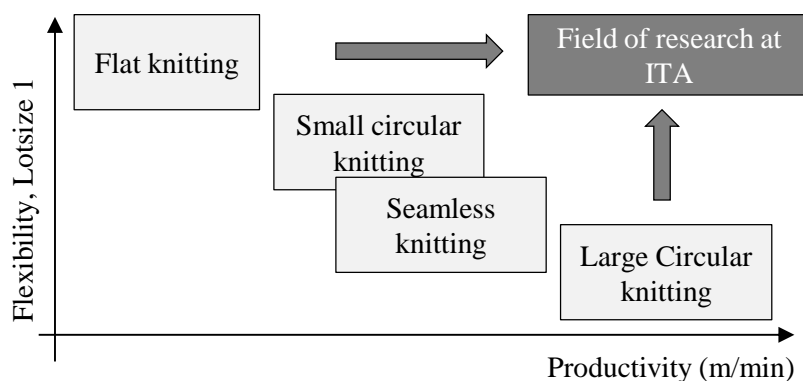
diameter less than 165 mm. The production of a sock's pendulum heel element is a special feature of the small circular knitting machine.

The loop height set by the sinker process parameter can be varied online for each course by flat and small circular knitting machines. By varying the loop height, the length of the fabric in wale direction increases. By knitting with different sinker heights in different courses, a three-dimensional shape can be realized. One product example of the sinker height variation is the circular knitting of jersey fabrics on separate needle beds with different setting conditions. Changing the mesh length from row to row results in a change of circumference. On flat knitting machines, the sinker height can be adjusted automatically during knitting. As a result, the variation in mesh length can be easily controlled thus leading to the creation of a 3D shape by changing the mesh lengths. [5, 19]

**Current large circular knitting machines** produce fabric tube being cut to a 2D fabric. So far, no three-dimensional elements can be knitted by large circular knitting machine. Neither the function of needle parking nor the pendulum function can be executed by this technology. Since this technology is used for mass production, the design of high productivity is first priority. As a result, the needles move continuously, whereas needle parking or pendulum functions would lead to a discontinuous movement. This discontinuous movement would decrease productivity to a non-profitable level of operational costs.

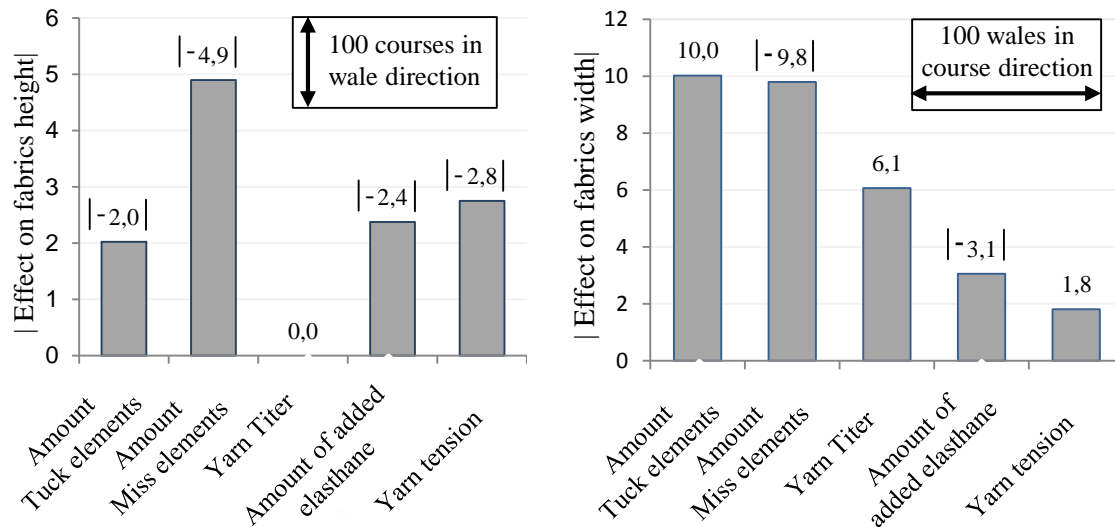
#### 4. Concept development

The development follows the VDI construction guideline 2221 and 2222 [20, 21]. One important requirement for the 3D development has been realizing 3D elements without changing the continuous movement character of large circular knitting machines. Also, the hardware modification is supposed to stay to a minimum in order to increase the chance for dissemination of the structure to industry. Jacquard large circular knitters are supposed to easily adapt to the new way of knitting with a minimum hardware investment. Ideally, 3D patterns should be realizable using a standard jacquard knitting machines (Figure 1).



**Figure 1:** Research field at ITA

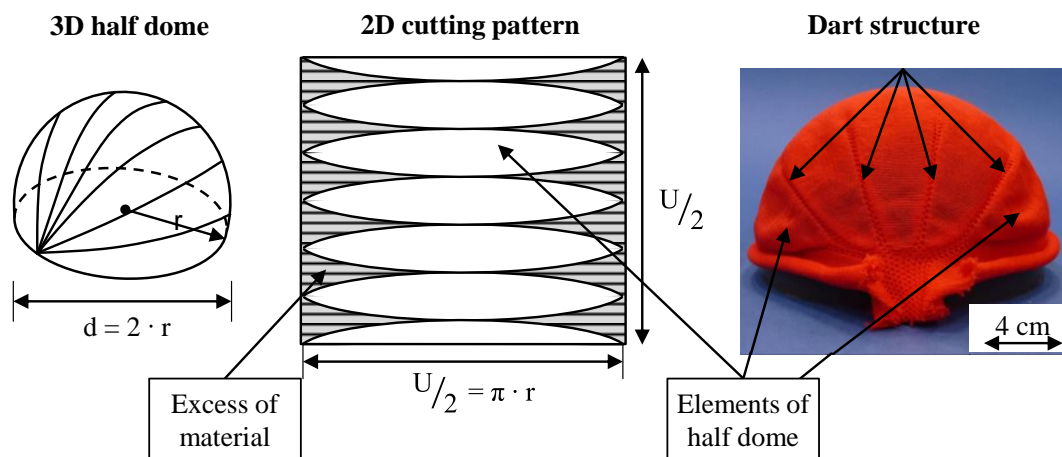
Firstly, current state of the art of creating 3D structures by the use of cutting pattern has been analyzed. In order to create a 3D volume out of a 2D fabric, so-called darts are integrated during the design process. Moreover, the interdependencies between different knitted structures – e.g. tight and loose patterns – lead to a “bulge” effect of the entire fabric. The interdependencies between five different (standard) pattern/structures have been analyzed specifically overall mesh density and drape effect have been studied in detail. As discussed, dimensions of weft knitted structures can be varied by process and machine parameters [22]. Figure 2 shows results of an executed effect analysis on single knit width and height by varying yarn tension, yarn elasticity, fineness as well as structural elements (tuck/miss). Moreover, the three dimensional behavior of the structures have been analyzed optically using the DRAPetest by Textechno Herbert Stein GmbH & Co. KG, Mönchengladbach and the image processing software ARAMIS of the Gesellschaft Optischer Messsysteme (GOM) mbH, Braunschweig. [8]



**Figure 2:** Effect analysis on process parameters' influence on width and height of single knit

Although varying process parameters can add or reduce the fabric volume, the range of variable dimensions is limited and will not lead to full material reduction or addition as desired. As a result, a pattern enabling the machine to produce the desired dart structure has been developed. A 3D half dome prototype according to desired 3D measurements has been knitted successfully (Figure 3).

The development uses polyester textured multifilament of three different fineness (1 ply à 167 dtex, 2 plies à 167 dtex, 3 plies à 167 dtex). Moreover, the investigations have been worked out on a single Jacquard large circular knitting machine at ITA, type BSJEM 1.3 manufactured by Beck GmbH, Albstadt, Germany. The E16 large circular knitting machine is 19 inches in diameter, is equipped with 960 needles and 24 knitting systems. The surplus material can be reduced without changing the continuous needle movement. The principle shown in Table1 has been consulted in order to develop the knitting of three-dimensional structural elements by large circular knitting machines. Since the development is based on programming, the hardware of the used standard jacquard machine has not been changed.



**Figure 3.** Prototype of a 3D large circular weft knitted fabric

Through this effort, we have shown that 3D knitting is possible using common large jacquard circular knitting machines. Future applications where such a technology can be readily used are medical, automotive, the sport textiles as well as the aerospace sectors.

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