From Handcraft to Digital: Transforming Spatial Crochet into Cutting-Edge Technology

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In the past decade, additive manufacturing processes have exhibited immense potential by pushing the boundaries of material exploration. Involving the construction of volumetric objects through adding flat knitting machines has gained recognition as an additive manufacturing technology since they possess the unique capability to directly fabricate three-dimensional articles from yarn. Nevertheless, while flat knitting machines have made significant strides in the production of three-dimensional textiles, they still face hurdles in handling intricate structures, achieving large-scale production, and accommodating a wide range of yarns. This article proposes crochet as a feasible substitute for knitting in multi-scale applications, owing to its inherent ability to create seamless three-dimensional shells.

Despite recent progress in computing crochet instructions, the absence of a digital fabrication technique for volumetric crochet within the framework of additive manufacturing remains a notable gap. This paper provides a thorough examination of the recent advances in computational crochet design tools. It then proceeds to analyze crocheting hand gestures and toolpaths to identify the pertinent design characteristics for a novel technology. Lastly, the paper introduces a pioneering digital fabrication device specifically designed for robotic crochet frameworks. This device underscores the notable advantages of crochet in comparison to other related fabrication methods.

Keywords: Robotic crochet; textile additive manufacturing; Digital craft; Three-dimensional crochet

1. Introduction

The revolutionary nature of additive manufacturing extends beyond its technological advancements. It introduces a new marketing perspective centered around mass customization, enabling the personalized adaptation of products while maintaining the efficiency and scalability of mass production. The textile industry is actively seeking digital manufacturing solutions that can cater to the demand for customized volumetric products.
Weft knitting machines are the most viable technology for the production of seamless volumetric items. Invented in 1589 by William Lee, the first knitting machine played a major role in the textile industry's industrial revolution (Raz, 1991). Developments such as the V-bed machine, tricot warp knitting, and electronic knitting selection led to increased accuracy and capacity in production. In 1999, the double needle bar wrap knitting machine revolutionized the field by creating 3D textile structures, providing significant economic advantages by eliminating cut and sew processes (Ray, 2012). Today, weft knitting is considered an advanced tool in the textile industry and serves as an additive manufacturing solution. Nonetheless, certain challenges remain. The input files of these machines are based on two-dimensional data, which means the CAD design must be flattened in order to be suitable for machine knitting. Yuksel (2012), McCann (2016), and Narayanan (2019) investigated methods for the transformation and representation of volumetric design files into flat knitting machine language and noted the topological limitations of this technology. Other limitations of flat knitting machines are the number of needles on the machine and the role of needle size in determining the outcome and yarn measurements.

The search for methods of volumetric textile design and fabrication has been highlighted in several recent studies dealing with the conversion of traditional textile crafts to 3D digital design and fabrication. Dörstelmann et al. (2014), Parascho et al. (2015), and Estrada et al. (2020) conducted multiple studies that involved the utilization of robotic winding of resin-reinforced yarn to construct various architectural constructions. McGee et al. (2019) investigate the field of robotic felting, seeking to expand the felt process beyond traditional fabrication by creating a designated robotic end-effector with multiple felting capacities in 2D and 3D. A different approach to robotic felting has been developed by Scott Hudson to create 3D soft items, customizing an FDM 3D printer head by adding a yarn feeder, needle, and pressing mechanism (Hudson, 2014). Another traditional technique named bobbin lace has recently generated interest due to its capacity to customize seamless 3D lace. Lisa Marks (2019) used Grasshopper parametric software to develop an algorithm for a personally customized lace medical bra (Marks, 2019) and Locatelli et al. (2017) explored how bobbin lace can be used in biomimicry with a large spatial control structure. Braiding, a similar handcraft, has also been examined parametrically, mainly in terms of architecture (Zwierzycki et al., 2017) using a set of tiles as the base of an algorithm to represent various braiding scenarios. These studies attest to a widespread interest in the exploration of digital techniques for the creation of volumetric textiles.

This study delves into a novel technology that uses crochet to create seamless volumetric textile shells. Crochet, an ancient handcraft, exhibits exceptional design freedom by enabling precise surface increases and decreases. The flexibility of crochet lies in allowing the hook to be inserted at multiple locations on a surface to create 3D items. The main reason for the current lack of industrial solutions based on crochet is the design freedom arising from the fact that stitches can be inserted at any point of the product (Seitz et al., 2021). The possibilities offered by the crochet technique for the fabrication of complex 3D items are currently limited by the scope of its practice as a manual craft.
2. **Background - Computational design tools for crochet**

Since ancient times, the creation of seamless three-dimensional textiles has involved direct production from a single continuous yarn. Initially, textiles were crafted manually. Over time, different types of needles emerged to create various fabrics. The advent of the nalbinding technique, akin to crochet and operating on the same principle, led to the production of the earliest seamless volumetric textile known as Egyptian socks (Rutt, 2003). The development of crochet appears to have progressed concurrently in Arabia, China, and South America. Evidence of crochet in Europe can be traced back to the 16th century in Italy, where it was known as a 'nun's work' (Potter, 1990). The earliest documented evidence of crochet in its present form dates back to 1780, represented by a pair of bootees (Karp, 2020). Throughout history, the crochet tool, characterized by a needle featuring a hook at one end, has undergone minimal changes, primarily in terms of the handle style. The relatively unchanged nature of crochet tools can be attributed to the pivotal role played by human hand movements, with the hook needle acting as an assistive tool. Despite the limited advancements in crochet tools, in recent years notable developments have been observed in the instructions and techniques employed in crochet work.

The transition of crochet from a traditional handcraft to digital fabrication involves two primary stages: computational design for the creation of a mesh and workflow, and the use of a physical fabrication tool to materialize the design file (Seitz et al., 2021). In recent years, significant progress has been made in the realm of computational design for crochet. Researchers have focused their efforts on developing simulations and visual representations of crochet stitch data and pattern instructions. Kucukoglu et al. (2013) presented a pioneer study in this field by decoding crocheted surfaces through the utilization of polyhedral models. A subsequent study by Çapunaman et al. (2017) presented a ground-breaking analysis of 3D crocheting and computational algorithms assigned to create crochet patterns out of 3D CAD files. This makes it possible to translate the surface sections into verbal descriptions, providing the crafter with text-based instructions as in conventional crochet. Guo et al. (2020) created tiles that demonstrate the different types of crochet stitches as building blocks for generating computerized 3D models. This novel method of crochet imaging provides an unprecedentedly realistic view of the expected outcome. The simulation system can function as a design tool to create patterns before time is invested in handcraft experimentation. Seitz et al. (2021) generated an editor for digital crochet patterns and developed it as an application with a user-friendly interface. Their software produces graphic instructions that relate to various types of crochet stitches and generate both 2D and 3D products. Following this research, Edelstein (2022) developed computational design tools that extract crochet text instructions from the input of a 3D model. In the realm of technical applications, Storck et al. (2022) introduced innovative models that employ finite element methods (FEM) for the analysis of crochet.

While the majority of studies in the field concentrate on computational approaches to crochet instructions, Perry (2022) took a different approach by developing a digital device capable of fabricating volumetric crochet. While mechanizing the stitch appears to be viable, the diameter of the resulting product is constrained by the dimensions of the cylindrical machine.

Despite the emergence of innovative digital tools for design, the production process of crochet remains predominantly manual. The transition from handcrafted crochet to digital fabrication necessitates the integration of various disciplines, including expertise in textile production, computational design, and architecture.
The objective of this study is to explore crochet as a unique fabrication technology with the ability to produce volumetric textile shells. With this in mind, the study proposes an innovative digital tool that positions crochet as a prominent technology within the realm of textile additive manufacturing.

3. Method

The confluence of digital design, fabrication, and handcraft has become a field of active research. According to Nitsche and Weisling (2019), the craft is a reference point for human-computer interaction capable of bridging the gap between handcraft and digital fabrication. Shaked and Dubin (2019) examined a framework that explores the transition of operations from the human hand to the robotic arm. This framework involves the conversion of a specific procedure into an iterative process encompassing various stages such as devising a case study, developing a toolkit, conducting experiments, and evaluating the resulting robotic artifact. The current research expands on this approach and formulates a protocol specifically tailored for crochet additive manufacturing fabrication (Figure 1).

![Figure 1: A linear robotic crochet fabrication, showcasing its application as an additive manufacturing technology](image)

The methodology employed in this study comprises three principal stages. In the initial phase, we engage in the manual construction of a large-scale structure using crochet techniques guided by textual instructions. This phase serves as a means to showcase both the morphological possibilities and challenges inherent in envisioning the digital fabrication process for large-scale crochet structures. The second phase of our study is dedicated to the analysis of the spatial path of the crochet hook. This analysis is essential in the transformation of a single stitch into a 3D digital path. Building upon this analysis, the final stage involves the design and development of a robotic tool capable of mechanizing and automating the manual process, enabling the creation of a sequence of single stitches.

3.1. Handcraft of volumetric crochet

The inherent spiral arrangement of volumetric crochet allows the production of various shapes by employing basic decrease and increase stitches. Decreasing involves merging multiple stitches, resulting in a reduction of surface area, while increasing involves creating multiple stitches from a single one, thereby expanding the surface area.

To represent the essential attributes of crochet as a comprehensive volumetric fabrication method, we conducted simulations by constructing a prototype using 3-4.7mm polyester ropes (Figure 2). This prototype serves as a potential case study for our new technology. The model showcases a crocheted surface stretched across three metal frames, representing the boundary conditions of a Costa minimal surface. The model was manually created using work instructions developed by means of the crochet algorithm proposed by Çapunaman et al. (2017).
The pattern code dictated a spiral workflow process, where each material layer relied on the preceding one, resembling the layering approach of FDM 3D printing. However, in manual crocheting the continuous spiral movements involved in creating large items become increasingly challenging due to the weight of the yarn, making manual rotation impractical. Confronted with the task of managing large-scale products, we recognized the necessity of integrating crocheting techniques while eliminating the need for product rotations. Keeping the product stationary during the crocheting process represents a paradigm shift. An additional innovative element is introduced by crocheting directly on a rigid frame. This approach, unique to crochet, holds potential applicability across a diverse range of fields, from architectural to medical applications.

This innovation represents a breakthrough in our comprehension of crochet's potential as a production process capable of operating on a scale beyond traditional handcraft techniques, exemplified by the creation of complex surfaces through a single maneuver, the utilization of materials on a large scale, and the seamless integration of rigid elements as integral components of the textile structure.

![Image](image1.jpg)

*Figure 2: Costa minimal surface installation, crochet process interlacing rigid frame (Photo credit: Shani Halevy)*

### 3.2. 3D tool path

To develop a digital fabrication technique for a handcrafted item, it is necessary to have a thorough comprehension of the manual process involved. A study conducted by Cho et al. (2022) examined the various levels of information by visualizing the intelligence of crocheting for educational purposes. They explored the difficulties involved in visually analyzing and presenting the two-dimensional aspects of crochet workflows, which inherently involve a significant spatial element.

In this study, we conducted a three-dimensional analysis of the crochet tool path for the 'single stitch,' which serves as the fundamental element for both surface decrease and increase (Figure 3). To capture the tool path, we utilized an Intel RealSense D405 Depth Camera with a short-range capability of 7-50cm. By recording the manual actions involved in performing the 'single crochet stitch,' we obtained depth images that enabled us to isolate the path of the hook tip in keyframes. The hook used in the analysis measures 146mm in length and 5mm in diameter and 16nm yarn composed of a material blend of 55% cotton and 45% PAC.
Figure 3: Left: Three-dimensional crochet hook head path as captured in-depth camera (MTRL 2023, Technion IIT)

The following steps were documented: 1) the starting point when the hook is inserted into the most recent open single loop; 2) the hook is inserted into an existing stitch; 3) the hook moves forward by 23mm; 4) the hook rotates 26 degrees to grasp the yarn; 5) the hook moves backward by 27 mm, pulling the yarn through the stitch forming an additional loop on the hook; 6) the hook moves forward by 24 mm; 7) the hook rotates by 17 degrees to grab the yarn; 8) the hook moves back by 20mm through the two loops completing the stitch and leaving a new single loop on the hook.

In conjunction with the recorded sequence of manual processes, we utilized the spatial toolpath of the manual crochet hook to establish the robotic fabrication process. The manual movement angle is reflected in its corresponding mechanized counterpart. The looping mechanism of the invention closely mimics the manual movement, ensuring that the yarn is wrapped around the hook in a manner that is similar to the manual movement (Figure 4).

3.3. Robotic Solution

Through a meticulous analysis of the manual crochet mechanism and the geometry of the toolpath, we established a set of design requirements that served as a foundation for the development of a patented digital fabrication tool for crochet (USPTO application #63/477,495). This tool is specifically designed to operate in conjunction with a 6-axis robotic arm for executing volumetric crochet. While the robotic arm moves row by row following a computerized path based on the textile pattern code, the device itself performs the actual crochet stitches. A computing unit ensures the synchronization of the arm's movement and the device's operation throughout the fabrication process.
The mechanisms of this system emulate the manual operation of crochet. The feed mechanism pulls the yarn from the cone, guiding it into the system while simultaneously regulating the tension. The looping mechanism creates loops and transfers them onto the stitching hook. The hook, in turn, executes the stitch by transferring the formed loop from the looping mechanism into the product, which is directed by the upper guides. These upper guides play a pivotal role in incrementally moving the fabric one stitch at a time and positioning it accurately for the subsequent stitch. The complete system, including the wires that transmit power and data from the controlling computer, is seamlessly housed within an external package (Figure 4).

The invention comprises a crochet head end effector designed for attachment to a typical robotic arm. This apparatus produces a series of single crochet stitches in accordance with a provided code, while the robotic arm manages the unique expansion of the crocheted surface (Figure 5).

Figure 4: Left: A looping mechanism designed to adopt the angles of the manual yarn gripping process. Right: Crochet robotic end effector mechanisms (MTRL 2023, Technion IIT)

Figure 5: Large-scale crocheting using a robotic arm and the patented crochet device (MTRL 2023, Technion IIT).
4. Discussion

This research introduces a new framework for translating handcraft techniques into digital fabrication, encompassing three main stages to explore the requirements for a digital crochet device.

In the first phase, a case study project was undertaken, requiring manual execution of a large and intricate topological surface. This involved utilizing ropes and a rigid frame. The project’s progress centered on a singular movement that followed a spiral progression, incorporating the addition and reduction of stitches to achieve a volumetric outcome. This approach emulated the anticipated workflow of a robotic system operating on a large scale.

In the second phase, emphasis was placed on capturing the spatial movement of the crochet toolpath. This was accomplished by documenting the manual operations and converting the gestures and toolpath into a digital format. The relationships between the vectors and angles of the crochet tool served as a foundation for determining the motions of the robotic mechanisms.

At the final stage, the process was dissected into sub-mechanisms that drew inspiration from manual actions. These sub-mechanisms were then re-integrated to create a unified unit capable of reproducing the handcraft. A prototype of the crochet system was meticulously designed and accompanied by detailed explanations of its operational components. The system has been patented, incorporating the concept of a robotic arm that supervises the overall progress, while the end effector carries out the actual stitching.

In contrast to conventional crochet techniques and other industrial solutions, our system utilizes a distinct methodology. Instead of moving the work object, our system holds it in a stationary position while the robotic arm handles the spiral movement. Additionally, the arm can be installed on a mobile platform, enabling its utilization in large-scale applications, while also remaining potentially adaptable for very small-scale tasks.

The lightweight nature of textile shells introduces uncertainties in their behavior as multi-scale material systems. To address this challenge, Oghazian and Vazquez (2021) have proposed a new approach that combines micro, meso, and macro scales within a cohesive design framework. The current study introduces the concept of crochet automation, which is applicable across various scales, ranging from delicate threads to large ropes.

5. Conclusion

This study introduces a novel perception of additive manufacturing within the textile field. The advancement represented by the system proposed above shares similarities with FDM three-dimensional printing, but instead of utilizing melting as an adhesion approach, it relies on connecting the material through crochet knots.

With the utilization of robotic crochet, it is possible to manufacture large-scale textile constructions seamlessly, surpassing the limitations of human handcrafters. Conversely, on a smaller scale, specialized crochet end-effectors can fabricate three-dimensional miniature products suitable for medical and other diverse applications. The robot’s capacities are no longer constrained by human limitations, but rather by the capabilities of the device and the characteristics of the materials. Additionally, the work capacity of the robot plays a vital role as it remains immune to human fatigue, allowing for prolonged periods of work at an accelerated pace with enhanced repeatability. While the
single fabrication device approach may require more time compared to knitting machines that employ a multi-head process, this limitation might be of greater concern to the garment industry, but of less immediate importance in sectors such as architecture, technical products, medical devices, and other markets.

This robotic solution enables the addition of a single or more stitches out of an existing one or a compilation of several existing stitches. This remarkable capability leads to significant surface alterations, a hallmark of crochet. This unique capability, using only the basic 'single crochet' stitch, results in dramatic surface transformations, as highlighted by Schipper (2022), who emphasizes crochet’s limitless potential for diverse surfaces and topologies.

The initial stage of crochet involves creating a row of chain stitches, followed by rows of crochet stitches. This first step requires a considerable level of complexity, which can be challenging to handle. However, this study specifically excludes this initial stage and instead focuses on the single crochet stitch as the primary building unit. In a previous study, we introduced a robotic method for producing chain stitches as a separate operation. For future research, our goal is to incorporate chain manufacturing into the remaining stages of the automated crochet workflow process.

The system showcased above is built upon the conversion of manual craftsmanship into a series of mechanical operations. Proposed here as an engineering design, its practical feasibility remains to be proven. Future research endeavors will involve constructing the system and acquiring hands-on experience to further evaluate its effectiveness.

References


https://books.google.co.il/books?id=r4FMPgAACAAJ


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