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Knotation: Supporting Exploration in Macrame Textile Crafting Through Parametric Motif Design

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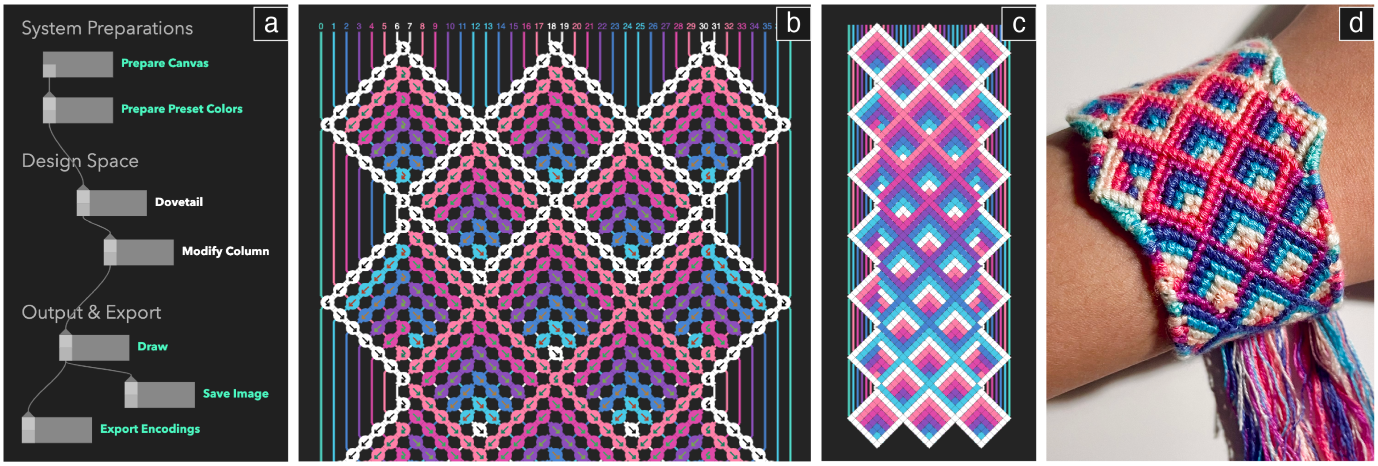

Fig. 1. Knotation is a macramé friendship bracelet pattern design system that supports parametric control of pattern structures and aesthetic features. Here we show a pattern designed in the system. a) The dataflow used to generate the pattern. We used a Dovetail motif module to create major characteristics of the bracelet design, and a Modify Column module for aesthetic adjustments. b) The generated Dovetail pattern. c) The zoomed-out pattern provides a design overview. d) Macramé friendship bracelet worn on wrist. Design discrepancies near the edges were improvised during the manual construction process.

***Abstract*—Macrame friendship bracelet creators produce ornate geometric motifs through the manual execution of sequential and iterative knot operations. By choosing different permutations of knot types and varying the number of operations in a sequence, creators fabricate different bracelet designs. Friendship bracelet patterns are often designed prior to fabrication using digital design tools. Existing digital tools require creators to manipulate designs at the level of each individual knot. As a result, creators must invest extensive manual effort in authoring and editing patterns. Furthermore, these tools limit creators' ability to manipulate higher-level design elements. We observed that friendship bracelets can be represented as repetitions of parameterized motifs rather than a series of individual knot operations. We present Knotation, a parametric design system to generate friendship bracelet patterns. The system abstracts existing popular motifs into modules that can be easily manipulated and modified by the user to produce visually interesting designs. Through a workshop with novice macrame creators, we show how our approach engages users with the craft using parametric design, and examine desirable aspects of Knotation's computational framework.**

***Index Terms*—Parametric Design, Textile Craft, Macrame**

I. Introduction

Many forms of textile production can be characterized by their algorithmic structure, where a craftsperson or a machine produces a textile by repeating and varying a set of discrete operations with one or more fibers. The procedural nature of textiles makes textile craft production well-aligned with parametric design. Thus far, computational fabrication researchers have examined the benefits of domain-specific computational representations for parametric design across a range of textile domains, including garment design [1], knitting [2], and weaving [3]. These parametric design tools enable craftspeople to manipulate high-level design abstractions rather than low-level fabrication operations, allowing for rapid modification of multiple complex elements through individual parameter changes [4]. Parametric design can, therefore, increase efficiency and allow craftspeople to rapidly explore variations and produce unexpected designs and properties [3]. Parametric tools can also enforce constraints that ensure the resulting design is feasible to fabricate for a given method [5].

We seek to extend parametric design to new audiences and identify new ways of integrating textile craft with parametric representations. Our focus is macramé friendship bracelets–a domain that has yet to be explored within digital parametric design. Friendship bracelets are a popular sub-form of macramé fabrication, created from a sequence of knots along multiple threads to produce colored strips of fabric with elaborate patterns. Each knot determines the ordering of the threads for subsequent knots. Craftspeople can produce elaborate geometric patterns by varying knot sequence and structure. Current friendship bracelet design workflows rely on the craftsperson's tacit knowledge of knotting patterns [6] or require manual drafting of individual knots [7]. Digital

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friendship bracelet design tools reproduce analog drafting techniques by representing a pattern as a connected row of knots, in which the user specifies each knot's structure and incrementally adds additional knot rows [8]. Such tools restrict the user to low-level, laborious design edits, hindering their ability to identify and manipulate high-level design patterns.

We observed that we could represent friendship bracelets as a series of parameterized design *motifs* rather than individual knot operations. We define a motif as a geometric shape composed of a sequence of knot operations that can stack upon itself or tessellate to form a larger pattern. We present *Knotation*, a parametric design system to generate friendship bracelet patterns for manual fabrication. Knotation abstracts popular motifs into modules that can be easily expressed and combined with user-defined control parameters. We represent bracelet patterns as a visual dataflow computer program with motif and motif modification operations as nodes. Our system enables creators to produce bracelets with non-rectangular forms while ensuring the results can be fabricated.

We evaluated Knotation through a design workshop with nine participants. We instructed participants in using Knotation and allowed them to design their own patterns and fabricate the results. We used this process to assess how Knotation enables design exploration for macramé production and to examine how our motif abstraction shapes peoples' understanding of friendship bracelet design constraints. We make the following contributions: 1) A novel interactive parametric design system, Knotation, which, to our knowledge, is the first parametric tool for macramé craft. 2) A parametric representation– motif– that provides a modular description of a repeating friendship bracelet pattern unit that can be parametrically manipulated to produce viable friendship bracelet knotting patterns. 3) A discussion of the benefits of parametric design for macramé production, identified through an open-ended design workshop. Through our discussion, we provide insights for future parametric design tools for manual textile crafts.

II. Background and Related Work

We identify the broader opportunities of parametric methods for textile production and provide an overview of the traditional friendship bracelet macramé craft workflows.

A. Parametric Tools for Textile Craft

The numerical, procedural nature of textile production is evident in pre-digital methods. Incan *quipus* stored numerical information in a decimal format [9] and early semi-automated looms used punch cards to encode weaving operations [10]. In more recent examples, skilled craftspeople used manual weaving to manufacture spaceship information storage modules [11], and researchers used crochet to investigate hyperbolic surface geometry [12]. Human-computer interaction (HCI) and graphics researchers have extended the numerical qualities of textile craft to develop computational textile design technologies. Within sewing, Berthouzoz et al. support sketch-based search and pattern interpolation by automatically parsing garment patterns [13], and Korosteleva and Sorkine-Hornung enable pattern manipulation through an object-oriented DSL [1]. Computational methods are commonly applied to ensure a given textile design is viable. Leake et al. formalized paper-piecing quilting to verify if an input pattern is pieceable [14] and McCann et al. created a compiler for machine knitting that converts shape primitives to machinable operations [5].

Researchers have studied parametric design for knitting and weaving. Knitting researchers have created computer-aided design (CAD) tools that enable the composition of parametric knitted primitives [2] or manipulation of procedural knit patterns through text-based [4] or visual programming languages [15]. For weaving, AdaCAD supports the parametric design of woven structures through a visual dataflow representation [3]. Our aims are similar to parametric knitting and weaving technologies. We seek to provide users with a higher-level design representation to facilitate exploration without manipulation of low-level instructions. Like AdaCAD, we rely on a dataflow language to represent patterns; however, our modules are specific to macramé.

Researchers have also explored parametric design for manual textile production. To support improvisational manual quilt production, PatchProv generates a process graph that determines available manual operations for quilting [16]. Hybrid Bricolage supports smocking through a catalog of modular parametric patterns [17]. PunchPrint enables parametric design for 3D printable substrates to guide punch-needle embroidery [18]. Amigo automates the process of generating manual crochet patterns from a 3D input model [19]. These works show how parametric design is still valuable for manual fabrication textile tasks. Similar to Amigo, Knotation targets a form of textile fabrication that cannot be machine-automated.

Macramé craft has not been previously explored within parametric textiles and is under-explored within HCI as a whole. Ku et al. use macrame knotting as one technique for creating circuitry as a component of on-skin electrical interfaces toolkit [20] and Poole and Poole explore tatting– a knotting technique with some similarities to macramé– to create e-textile interfaces [21]. Knotation is the first macrame-specific parametric design system. Developing Kotation required building domain-specific parametric representations for friendship bracelet knot structures and a verification method for ensuring that resulting patterns can be fabricated.

B. Macramé Friendship Bracelet Structure

Macramé is the craft of decorative knotting. In contemporary craft, macramé often appears as wall hangings [22], [23], sculptures [24], [25], garments [26], [27], and jewelry [28], [29]. Friendship bracelets are a popular folk art variation of macramé. They are created from a limited subset of knotting techniques and usually comprise fabric belts worn around the wrist. We focus on "Normal" type friendship bracelets, where knots are tied from two neighboring threads and connected to each other in diagonals. Typically, all threads are knotted onto the others, creating the design of the textile [30]. Below, we detail friendship bracelet construction.

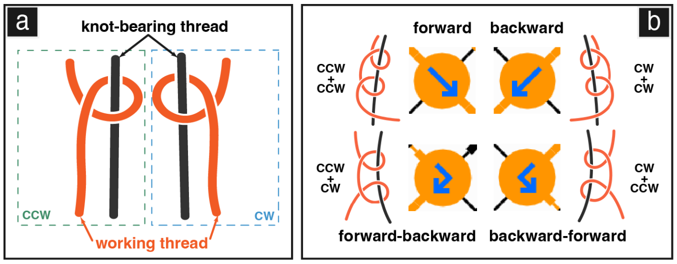

Fig. 2. Knot structures and representation. a) A counterclockwise (CCW) and a clockwise (CW) half-hitch knot. The working thread of the CCW knot is its left thread. The working thread of the CW knot is its right. b) Combining the two half-hitch knots results in the four distinct types of double half-hitch knots: *forward*, *backward*, *forward-backward*, and *backward-forward*. In friendship bracelet patterns, each knot is represented by a circle and a pair of input and output threads. The knot and its working thread share the same color. The arrow indicates knot type and the working thread direction.

1) Basic Hitch Knots: Half-hitch knots are components of the set of basic knots in friendship bracelet fabrication. A half-hitch knot is created from two adjacent threads, where the working thread is brought over and then under the knot-bearing thread. The creation of a counterclockwise or clockwise half-hitch knot is contingent upon the selected working thread (Fig. 2). A single half-hitch knot is insecure on its own and is reinforced by tying a second half-hitch knot to form a double half-hitch knot. The combination of clockwise and counterclockwise half-hitch knots results in four distinct types of double half-hitch knots: *forward*, *backward*, *forward-backward*, and *backward-forward* (Fig. 2b). These four types are the foundation of friendship bracelet fabrication. Friendship bracelet creators must select different knot types in their designs to achieve the desired visual and structural qualities. The knot type affects aesthetics by designating a knot's bearing and working threads. Each knot takes on the color of its working thread. Structurally, the knot type impacts the set-up of its downstream neighbors' working or knot-bearing threads. Since knots in a friendship bracelet are executed sequentially, a change in knot type will alter input threads of subsequent knots and, consequently, the bracelet's aesthetics.

2) Pattern and Motif: A friendship bracelet pattern structures a series of knots to form a larger design composition. Friendship bracelet patterns are typically visually represented as a grid of connected knots, where each knot connects to its four diagonal neighbors– Fig.1b is an example. When making friendship bracelets, knots are executed sequentially from top to bottom. We observed that friendship bracelet patterns often feature a primary geometric element that is repeated throughout the pattern. The complexity of the geometry can vary, but it is always identifiable as one of the most salient design elements within a pattern. Coupled with the creative use of colors, it invokes strong visual interest. We refer to these repeated geometric elements as *motifs*. We define a motif as a geometric shape composed of a sequence of knot operations that is able to stack upon itself or tessellate to form a larger pattern. The concept of motifs provides a higher level of abstraction to help us think about bracelet patterns as iterations of the same knot sequence instead of collections of individual knots. Motifs not only enable us to identify a pattern's prominent characteristics, but they also allow patterns to be more easily segmented, understood, and parameterized.

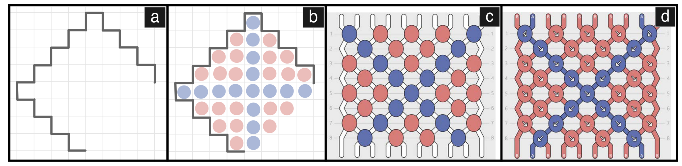

Fig. 3. Pattern drafting workflow. a) First, draw the bracelet outline on gridded graph paper. The outline determines the number of threads and rows. b) Next, sketch the bracelet design within the outline. c) Then, in an empty pattern, color in the knots according to the design sketch. d) Determine the appropriate knot type for every knot. This step is challenging due to constraints of knot structures, and the craftsperson must also maintain accurate thread continuity. It's possible for a design to have multiple solutions or none at all.

C. Friendship Bracelet Pattern Design Tools

Craftspeople learn knotting techniques from in-person instruction, books, or online communities. The website BraceletBook.com hosts a database of bracelet patterns, tutorials, and forum discussions submitted by thousands of active users [30]. Craftspeople draft their own bracelet patterns to create original designs. To manually draft a pattern, the craftsperson first sketches the shape of their desired design on a diagonal grid (Fig. 3a, 3b). They convert this design to a knotting pattern by assigning individual knots to each point on the grid so that all knots together achieve the corresponding appearance of the original design (Fig. 3c, 3d). This process offers a high degree of flexibility but requires significant skill and effort to accurately reproduce the design and ensure fabricability.

Several online friendship bracelet communities have developed digital pattern generators. These tools provide a rectangular starter pattern that consists of only *forward* knots. The user can adjust pattern dimensions by adding or removing threads and rows. By clicking on any individual knot, the user can cycle through all basic knot types, thus altering the pattern to move closer to a desired design. The user can also set the color of any thread in the pattern. Digital pattern generators provide an advantage over analog drafting because they automatically reflect cascading changes anytime a knot or thread is altered; however, they share many other limitations of manual design. The largest editable unit remains the individual knot. While the ability to edit every knot allows the user maximum customizability, it also requires extensive labor to define or alter new patterns because the user must manually adjust or define each individual knot. When the user increases pattern dimensions or the size of geometries in the design, the number of repetitive mouse clicks the user needs to make increases dramatically, regardless of whether the design becomes more complex. As a result, visualizing or manipulating higher-level design elements in such tools– e.g., "the big picture" of a design– remains difficult. Documented pattern drafting workflows using digital generators [7], [31] merely extend the manual workflow by adding a finishing step to input the manual pattern into the generator.

III. Knotation System Design and Implementation

Knotation is a parametric design system for drafting new friendship bracelet patterns. Using Knotation requires prior knowledge of basic structures in friendship bracelets, as described in Section II-B, but does not require prior programming or extensive macramé knowledge. By centering motifs as a high-level component to manipulate, we aim to encourage the user to consider major characteristics of the bracelet design first as they are drafting a pattern. We describe the Knotation system interface and the programming modules and illustrate workflows through sample applications.

A. Knotation Design Objectives

To guide the design of Knotation, we evaluated the limitations of existing digital friendship bracelet creation methods and the affordances of parametric design. We built upon our concept of motifs to develop a parametric system for friendship bracelet pattern drafting with the following objectives:

1) Support digital friendship bracelet design that is feasible for people without extensive software experience.
2) Enable high-level digital manipulation of friendship bracelet design patterns.
3) Enable rapid exploration and iteration of the pattern design during the drafting process.

B. Programming Environment

We developed Knotation in Nodes.io– a visual programming environment where the user composes dataflows using JavaScript code modules to produce visualizations and render graphics. Using a dataflow model aligned with our goal to prototype parametric representations of friendship bracelet patterns, since dataflow has proven to be successful in crafts and design fields, such as Grasshopper for architecture design, and AdaCAD for designing woven structures [3]. Each code module can be equipped with `in` and `out` ports to handle input and output data. Connections between modules are established by dragging an `out` port of one module to an `in` port of another. Data generated by the parent module is passed down to its children. In Knotation, the user does not interact with textural code directly but instead manipulates pre-written modules to generate and edit their patterns.

C. Interface

Knotation's user interface comprises three areas: the *graph editor*, *the viewport*, and the *inspector*. The graph editor (Fig. 4a) is the user's primary drafting area. The user is provided with a preset color palette and template modules: motifs and modifiers. Function modules in *Canvas Preparations* and *Output & Export* establish the beginning and the end of the pattern generation dataflow. To generate a friendship bracelet pattern, the dataflow requires a motif module, so the user selects one from template motifs and duplicates it in *Design Space*. Next, the user connects the `out` port of the function module `Prepare Preset Colors` in Canvas Preparations to the copied motif module `in` port. The user may continue to chain any number of modifier(s) after the motif. Lastly, the user connects the `out` port of the last module in the Design Space to the `in` port of the Draw function module in Output & Export, and completes the dataflow. The completed dataflow generates a bracelet pattern, which is rendered in the viewport (Fig. 4b). Any modification in the dataflow prompts the pattern to be redrawn to reflect changes. In the inspector (Fig. 4c), the user can adjust the location and the display size of the pattern with sliders and pick the background color. To assist the user in identifying threads and knot positions on the pattern, thread indices and a coordinate grid are also rendered by default but can be toggled off. When the user clicks on a module, the inspector switches to show module-specific options enabling the user to edit parameters specific to the module.

The system supports two Output & Export features. The "Save Image" button in the inspector takes a screenshot of the viewport to save the generated pattern as a `PNG` file. The user can also find an "Export Pattern Encoding" button. Knotation converts the generated pattern to a text encoding that is compatible with the existing pattern generator on BraceletBook.com. This enables the user to edit their pattern at the knot level in a direct manipulation application if desired.

D. Parameterized Motifs

Motifs are integral to defining friendship bracelet aesthetics and pattern structure. Many bracelet patterns are created from the tessellation of just one motif. We sought to enable the user to quickly extend an individual motif into a digital friendship bracelet pattern with easily adjustable tiling by developing parametric motif representations that can be manipulated within the Knotation system. We focus on four commonly utilized motifs in friendship bracelet designs: the *Candy Stripe,* the *Chevron*, the *Diamond*, and the *Dovetail*. We chose these because they demonstrate a progression in motif structural complexity and use different tessellation strategies.

We developed a module for each motif to provide parameterized control of its geometry. The motif size parameter is defined by the number of knots that comprise a motif's key geometric characteristics. For example, the Chevron is an arrow-like shape formed by joining a diagonal row of *forward* knots and a diagonal row of *backward* knots of equal length. Therefore, a Chevron with `n` *forward* and `n` *backward* knots has a size parameter of `n`. Similarly, a Diamond of size `n` has $n \times n$ knots forming a square shape. In Knotation, the user controls motif size from the inspector with a size parameter slider (Fig. 4d). We defined the Knot object to store a knot type and two input thread indices. It computes two output thread indices. We represented each motif as a 2D array in which Knot objects are populated corresponding to motif geometry. A Thread object is implemented to store thread index and its hex color value. Each motif module maintains a threads array.

To extend a motif into a pattern, the user can generate vertical and/or horizontal repeats with sliders in the inspector (Fig. 4d). We developed specialized extension logic for each

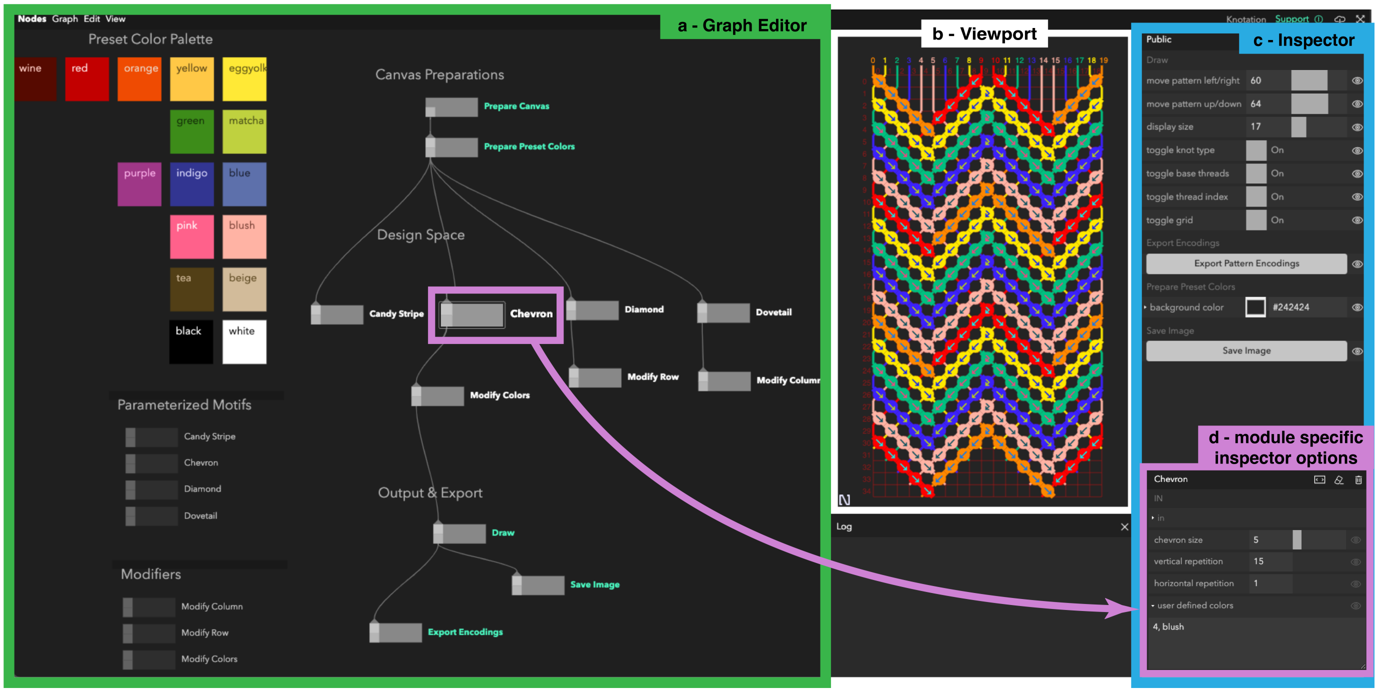

Fig. 4. Knotation user interface. a) The graph editor is where the user creates dataflows to draft patterns. We provide four sample workflows to demonstrate module functionalities. We also provide a preset color palette (top left) and standalone template motif and modifier modules (bottom left). b) The viewport displays the generated pattern. c) The inspector contains parametric control options. By default, it shows toggles to change the appearance of the pattern in the viewport and buttons to save the pattern as an image or an encoded file. d) The inspector can display module-specific options. E.g. The user selects the Chevron module. The inspector switches to the chevron size slider, vertical and horizontal repetition sliders, and the input box for user-defined colors.

motif module to preserve the pattern structure. For example, adding one vertical repetition to the Chevron motif adds a row to its array representation. A copied set of Knot objects are merged directly under the first Chevron. Horizontal repetitions generate copies of the motif array and merge to its right. An additional column of *forward-backward* knots is generated between each horizontal repetition to keep the pattern connected. The Diamond module generates additional diamond motifs between each vertical and horizontal repetition to complete the tessellation. The user can select different degrees of overlap to adjust the tiling density using vertical and horizontal overlap toggles in the inspector. Likewise, the Dovetail module generates additional dovetail motifs for tiling. This behavior prevents large gaps across the pattern.

For motif coloring, we generate each motif with a color gradient by default. The user can further customize aesthetics by specifying the thread index and the name of a preset color in the inspector. Our parametrized motif modules enable the user to create friendship bracelet patterns from a single motif and precisely control the number of times and how it appears in the pattern. Subsequently, the user has control of both the visual design and the overall dimensions of the bracelet pattern. In contrast to existing pattern drafting workflows, the user doesn't have to design each knot in a pattern, significantly reducing the amount of labor. Additionally, Knotation ensures motif correctness at a high level by automatically calculating the relationships produced between individual knots by a specified vertical and horizontal repeat.

E. Modifiers

We developed three modifier modules in the Knotation system: *Modify Row*, *Modify Column*, and *Modify Color*. Modifiers are used in conjunction with motif modules. While motifs parameterize and allow repeats over a larger design element, modifiers provide parameterization over individual rows, columns, and threads, granting the user the ability to create edits that span multiple motif repetitions.

With Modify Row and Modify Column modules, the user can change all existing knots in any row or column in the pattern to be a specific knot type. As described in Section II-B, knot type determines the color of the knot, and knot type changes impact neighboring knots. Modifying knot types for an entire row or column allows the user to quickly enact cascading changes to the design. We implemented a symmetric toggle to mirror row or column modifications for horizontal and vertical symmetry. To apply a Modify Column, the user makes a duplicate of the template module and inserts it to the dataflow. Selecting the module brings up an interface in the inspector for module parameters. The user first specifies a column by its index number by referencing the coordinate grid. Next, the user selects an option from the four basic knot types. The module assigns the selected knot type to all existing knots in the selected column of the pattern's 2D array representation. The module performs a recalculation for every knot in the pattern and updates their input and output threads in order to reflect the effects of the knot type change. The Modify Row module functions identically for selected rows. The Modify Color module enables the user to change thread colors. The user selects a thread by index and chooses a new color for it using a color picker. The user is constrained to modifying threads instead of specifying a knot color change. Since multiple knots can be connected by the same working thread, changing the color of any one knot necessitates changing its working thread color and all other connected knots as well. We set thread color defaults for the motif modules that highlight the shape of the motif. For that reason, the Chevron, the Diamond, and the Dovetail are coded to enforce motif symmetry, so color customization is limited when working solely in the motif. Modify Color expands the aesthetic control of the user to violate this constraint and use colors to conceal the shape of the motif, create larger color blocks, and create asymmetrical visual contrast.

F. Maintaining Pattern Validity

Two inherent constraints of friendship bracelet patterns are 1) every knot's appearance is determined by its input threads and its knot type, and 2) all threads must remain continuous throughout the pattern. Knotation enforces these constraints to ensure pattern validity during the user's drafting process. Compared to existing generators that operate at the knot level, Knotation is able to produce more substantial cascading pattern changes. In order for the user to see design modifications immediately, Knotation automatically re-renders the bracelet pattern. The system iterates through the pattern's array representation to catch and correct thread inconsistencies between neighboring knots. For example, the left input thread index of a knot must be the same as the left upstream neighbor's right output. However, thread indices may become mismatched after parameter updates, violating thread continuity. Therefore, the system corrects the mismatched knot by updating its input threads with its upstream neighbors' current output threads. The knot then recalculates its own output thread indices as well. This action ensures both accurate design appearance and thread continuity throughout the pattern. As Knotation generates patterns from motifs, resulting patterns can be non-rectangular and have empty areas along edges of the pattern. This poses additional rendering challenges. When a knot is missing an immediate upstream neighbor, the system must seek upwards in the array representation for the nearest predecessor to find its corresponding input thread(s). Knotation renders threads continuing through empty areas between knots to provide a more readable and intuitive pattern image.

G. Drafting a Pattern in Knotation

We present an example workflow for creating and modifying a pattern in Knotation. To draft a friendship bracelet pattern in Knotation, we first completed the dataflow that generates the pattern image in the graph editor. We need to provide our choice of motif module and modifiers in the Design Space. At a minimum, the dataflow needs to connect from Canvas Preparations to a motif module and then to Output & Export for a design to be visualized. Modifiers are optional. We

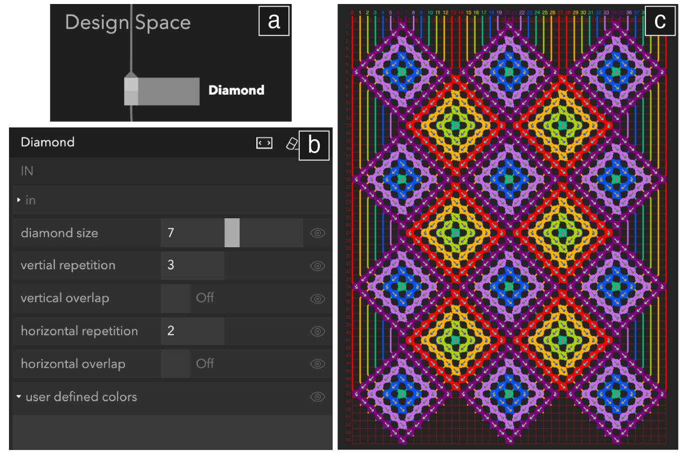

Fig. 5. A simple diamond motif pattern. a) We used one Diamond motif and no modifier in the dataflow. b) Parameter settings of the Diamond motif module. We set the diamond size to 7, and with 3 vertical repetitions, and 2 horizontal repetitions. c) The resulting pattern rendered in the viewport.

selected the Diamond motif as the starting point for our pattern by duplicating a template Diamond module to the Design Space and connecting it to the dataflow. From the inspector, we increased the module parameter diamond size to 7, vertical repetition to 3, and horizontal repetition to 2. We chose not to have any vertical or horizontal knot overlap when tiling the motif. Additionally, we did not alter motif colors, as we were satisfied with the default color gradient. As a result, the Diamond motif was extended to a pattern that had a total of 55 rows of knots and would require 42 threads to make. Fig. 5a and 5b show Design Space dataflow and motif parameters, Fig. 5c is the rendered pattern in the viewport.

By modifying a small number of parameters on a single module, we can quickly describe a complex bracelet pattern with dimensions to our specifications. We customized the structure of our diamond pattern extensively by applying multiple modifier modules. First, we inserted a Modify Row module into the dataflow, chained after the Diamond module. We found that changing the middle row of a diamond motif yielded a drastic flip of color (Fig. 6b). In the Modify Row's inspector panel, we selected row 6 and changed its existing knots to *backward* knots. We were curious what the pattern would look like if the row modification was applied throughout the diamond tiling. We inserted two more Modify Row modules into the dataflow, applying the same knot type change to rows 13 and 20. Toggling on the symmetric feature in all three modifier modules facilitated mirroring changes to the bottom half of the pattern, thereby reducing the number of required modifiers in total. Fig. 6c displays that all three Modify Row modules together generated a triangular checkered aesthetic.

Next, we explored column modifications. By inserting a Modify Column module into the dataflow, we changed all existing knots in column 17 to *backward-forward* and mirrored it in column 23 with the symmetric toggle (*backward-forward* knots are mirrored to *forward-backward* so that the pattern appears left-right symmetrical). This modification

TABLE I
WORKSHOP PARTICIPANTS PRIOR EXPERIENCE

ID	Prior Textile Exp.	Prior Macramé Exp.	Primary Digital Design Tools	Prior Coding Exp.	Visual Programming Exp.
1	>5 years	Friendship bracelets	Illustrator, Photoshop	No experience	TouchDesigner
2	<1 year	Friendship bracelets	Clip Studio Paint, Procreate, Fusion 360	>5 years	N/A
3	>5 years	No experience	Illustrator	>5 years	N/A
4	>5 years	Friendship bracelets, plant pot holders	N/A	No experience	N/A
5	<1 year	Friendship bracelets	Illustrator, Photoshop, Blender, Canva	1-2 years	TouchDesigner
6	>5 years	Friendship bracelets	Illustrator, Procreate, GIMP, Inkscape, Blender	>5 years	N/A
7	3-5 years	Friendship bracelets	Illustrator, Fusion 360	<1 year	Node Tools in Blender, MakeCode
8	No experience	No experience	Illustrator, Photoshop	<1 year	N/A
9	No experience	No experience	Illustrator, Photoshop, Rhino	>5 years	Grasshopper

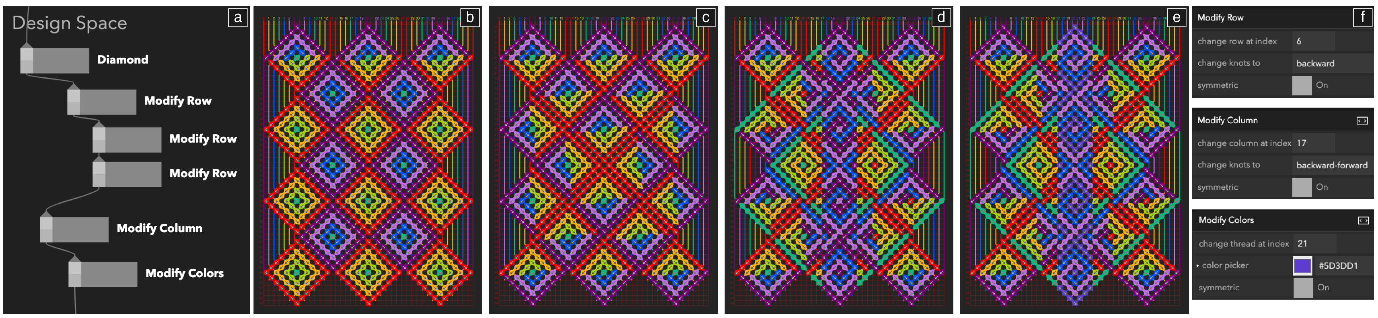

Fig. 6. The variegated diamond motif pattern. a) Dataflow to generate the pattern. b) The pattern after we applied the first Modify Row module to change knots in row 6 to *backward*. c) After applying the same row modifications in rows 13 and 20 with symmetric toggled on, the triangular checkered appearance was seen throughout the pattern. d) The pattern was further disrupted with a Modify Column. e) The pattern after we applied a Modify Colors to recolor threads 21 and 22 to violet. f) Modifier modules parameter settings.

visually isolated and highlighted the center columns of the pattern. Additionally, it rearranged input threads for knots in neighboring columns, causing a cascading effect that distorted colors in large parts of the pattern. Fig. 6d demonstrates the substantial change in the pattern's appearance after applying Modify Column. To introduce some visual harmony back to our design, we applied a Modify Colors module to change threads at index 21 and 22 to a violet color (Fig. 6e). Fig. 6a shows the dataflow and how each modifier introduced additive changes to produce our final pattern.

IV. EVALUATION

A. Methods

We conducted an in-person, four-hour design workshop to examine how users interact with Knotation. Through the workshop, we investigated two research questions:

1) How do motifs benefit the user's understanding of constraints in friendship bracelet pattern design?
2) How does Knotation support the user's design objectives?

The workshop enabled us to assess how participants used Knotation to pursue personal design and fabrication objectives. We advertised the workshop through social media, local craft spaces, and physical flyers around the university. We solicited participants interested in both designing friendship bracelet patterns and in parametric or digital design, though prior experience was not required. A total of nine participants attended the workshop, aged 25 to 64. Table I lists participants' prior experience with craft, digital design, and programming. During the first 1.5 hours, participants were introduced to friendship bracelet craft practices. We showed participants how to make knots and how to interpret friendship bracelet patterns. Participants were given time to learn and practice knots. Next, we spent 30 minutes introducing Knotation and demonstrating a sample workflow. We then gave participants 1.5 hours to draft patterns of their choice in Knotation and to fabricate friendship bracelets according to their own designs. We conducted a 30-minute group discussion at the end of the workshop about participants' experiences. We collected data through pre- and post-workshop surveys and audio-recorded group discussion. We photographed participants' designs in Knotation and the bracelets they produced.

B. Results

1) Product Outcomes: All participants were able to independently design at least one pattern in Knotation during the open design and making session. All participants fabricated or partially fabricated at least one friendship bracelet. Participants who only partially fabricated a bracelet ran out of time to complete making the bracelet due to the time constraints of the workshop. All except one participant stated that they were excited about finishing their bracelet after the workshop.

Participants used Knotation to design multiple friendship bracelet patterns in the time allotted. Five out of nine participants were able to create more than one bracelet pattern during the workshop. In the post survey, two participants stated

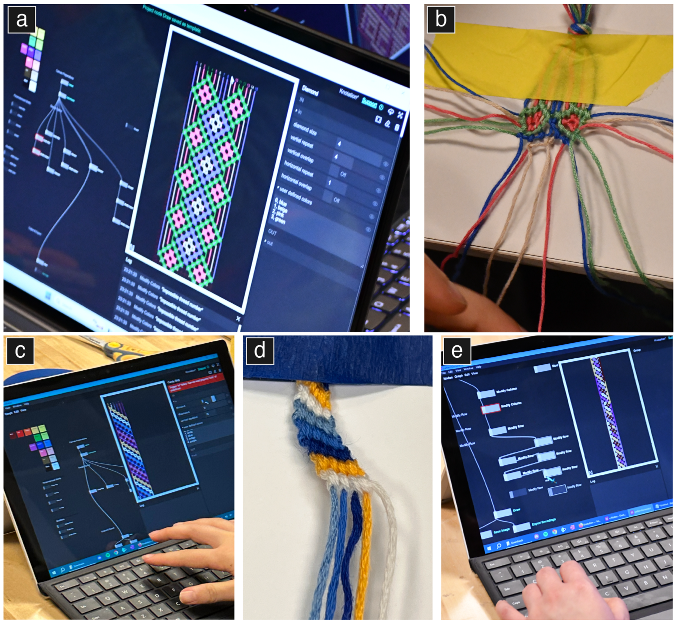

Fig. 7. a) Participant 4 created their pattern with the Diamond motif module alone. They customized motif colors through textual input. b) The partially fabricated bracelet made according to participant 4's pattern. c) Participant 2's pattern started from the Candy Stripe motif module. d) A segment of the initial pattern manually fabricated. e) Participant 2 adds multiple modifier modules to the dataflow.

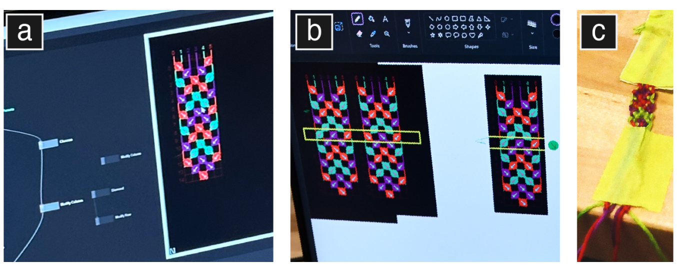

Fig. 8. a) Participant 9 drafted their pattern using a Chevron and a Modify Column module. b) Using a Modify Row module, participant 9 changed knots in row 7 to *backward*. The participant noticed colors in row 7 became asymmetrical. By comparing the pattern after and before the modification, they were able to see how the knot color can be changed by knot type. They discovered that changing the rightmost knot in row 7 to *forward* can achieve the color symmetry they desired, though Knotation did not support modification of singular knots. c) The partially fabricated bracelet.

that they created a total of four patterns using Knotation, one participant created three patterns, and two participants created two patterns. Participants were more likely to start with the Candy Stripe motif and the Diamond motif modules. Only two participants used the Chevron motif. Three participants stated in the post survey that they were intrigued by the Dovetail motif, but did not create patterns with it. Eight participants customized colors in their patterns to match the physical threads they chose, either by defining colors in the motif module or by using the Modify Colors module. Three participants did not use any modifiers; for example, participant 4 drafted the pattern in Fig. 7 solely using a Diamond motif module. They generated one horizontal and four vertical repeats, and customized the motif's color according to their threads. In Fig. 7b, the participant is making the bracelet according to their pattern. Two participants had more then 10 modifiers in the dataflow to achieve their design. For example, participant 2 created a "braid" pattern. Fig. 7e shows how they achieved this by adding additional Modify Rows to the dataflow.

2) Participant Experience:

a) General Reactions: Most participants responded positively to the Knotation system. Five out of nine participants agreed or strongly agreed with the statement, "I enjoyed using Knotation to design friendship bracelet patterns." The rest were neutral. Fabricating friendship bracelets from personalized patterns drafted in Knotation by participants themselves was enjoyable to five participants. Six out of nine participants agreed or strongly agreed that they were able to create visually interesting patterns. Four participants stated they were satisfied with the patterns they designed in Knotation. A correlation was observed in post survey data between participant satisfaction and how closely a participant's pattern matched their desired aesthetic. In discussion, participants described their appreciation for Knotation's novel approach:

> "I've never really seen computer programming applied to textiles before... There [are] a lot of things you can do with software I haven't considered you could transform into the real world." - Participant 2.

Participants also felt that the direct connection between digital pattern design and physical friendship bracelet fabrication was important. Participant 5 enjoyed "having two separate mediums of creativity" to approach creating friendship bracelet designs. Participant 3 explained that the digital representation of knots and patterns aided them in understanding the physical making process as a beginner in the craft.

b) Software Use: Participants who drafted fewer patterns during the workshop struggled with understanding or interacting with user interface elements. Participant 6 created just one pattern and said, "There was a learning curve on figuring out how to connect nodes and add new colors, columns, and rows." Several participants also disliked that they had to click a module to access its parameters in the inspector when modifying it. They felt this disrupted their design process and caused them to lose track of edits made to the pattern.

While the interface posed some usability challenges, participants found Knotation primitives valuable. Six out of nine participants stated that modifiers were useful or helpful to their designs. In particular, participants appreciated having different options for color customization in Knotation. During discussion, participants were in agreement that it was important to have the digital pattern thread colors correspond to the physical threads they used to fabricate bracelets. Two participants commented on the process of transitioning from Knotation to the manual fabrication process. They stated that it was sometimes difficult to keep track of the location of the knot they were working on in the pattern.

Despite the range in the number of patterns drafted by each participant, the majority felt they were productive. Eight out of nine participants agreed or strongly agreed with the statement, "I'm happy with the number of patterns I've created during the workshop." Furthermore, many participants felt they were able to make meaningful edits. In the post survey, four participants agreed or strongly agreed they were able to rapidly edit and tweak their patterns. During the group discussion, Participant 5 explained that Knotation enabled them to "think about more designs and play around with different ideas I could have."

The dataflow environment in Knotation received some critiques. Both Participant 3 and Participant 8 preferred to avoid dataflow programming environments. Participants with prior dataflow experience in other domains noted benefits to Knotation's dataflow, including automatic saved work for archiving ideas; however, they also felt that the design process in Knotation represented as a linear sequential chain, which contradicted their intuition about dataflow as a tool for creating networks of operations.

c) Support of Craft Insights: Knotation helped participants understand the structures and constraints of friendship bracelet patterns. When describing a motif in their own words, many participants understood it as a repeatable pattern unit:

> "A motif is a design feature that repeats and can be utilized in various ways, almost like a word or letter in language. Motifs can be combined or split apart in various contexts, can function differently but still maintain their distinctive qualities." - Participant 1

> "[A motif] can best be evaluated at the macro level - looking at the bracelet as a whole and analyzing what shapes and patterns stand out." - Participant 7

In the post survey, all participants agreed or strongly agreed that they understood how knot type affected thread direction. Participants indicated Knotation's ability to visualize the effects of different knot types and immediate feedback on parametric pattern modification supported their understanding of knot structures and their constraints. Participant 9 stated that "[Seeing how] everything kind of propagates, it helped me understand how everything is so interdependent." Fig. 8 illustrates participant 9 encountering conflicts between knot constraints and their intended bracelet design. By observing the changes, they gained a deeper understanding of how knot structures function.

Moreover, Knotation enabled some participants to draft complex patterns. Patterns with the Diamond motif are more structurally complex than other motifs, and thus more difficult to understand and design. At least two participants, with no prior experience, created patterns using the Diamond motif. Assistance provided by motif modules enabled participants to see motif complexity as a feasible challenge. Participant 7 noted that the benefits of the system became more apparent when dealing with more complicated designs: "I thought it was great as it was able to give me custom patterns that I would not have been able to figure out on my own as a beginner."

d) Requests for future features: Participants experienced limitations of motif and modifier modules and suggested future features. Regarding modifier modules, participants asked for more flexibility and automation. This included the ability to partially modify rows and columns or edit a single knot. Other participants wanted to apply modifications over larger sections of their pattern to avoid needing multiple modules. Finally, participants expressed the desire to include multiple motifs in one pattern. Some proposed a potential implementation to vertically or horizontally connect pattern segments generated by different motif modules. Others suggested adding motifs to fill in specific sections of a main pattern. Participants also suggested support for user-defined motif modules.

V. Discussion

We discuss the outcomes of our workshop in relation to our research questions. We address R1 by examining how motifs enabled participants to understand constraints and strategies for friendship bracelet fabrication. We address R2 by analyzing how Knotation supported participant design exploration in ways not feasible in analog and non-parametric digital design. We follow by identifying ways to further improve the usability of future parametric systems for macramé craft.

A. Friendship Bracelet Craft in relation to Parametric Design

Currently, macramé fabrication cannot be automated and requires manual construction. It is, therefore, critical that a designer understands how friendship bracelet structures are fabricated and, as they start to design bracelet patterns, what structures they should manipulate and why. We argue a successful design tool should reveal rather than obscure how design operations translate to manual construction operations. Our evaluation shows that introducing motifs as a high-level abstraction of pattern characteristics benefited how participants understood friendship bracelet patterns. Rather than conceptualizing a friendship bracelet pattern as a web of knots, our results suggest that Knotation encourages craftspeople to think about friendship bracelet patterns from the perspective of parametric design. Participants grasped the concept of motifs quickly and proposed creating their own motifs. Furthermore, participant comments indicate that the parametric exploration afforded by Knotation not only facilitated design variation but also enabled participants to actively explore cascading behavior that is characteristic of friendship bracelet fabrication as a whole.

In addition to understanding overall knot structure, skilled friendship bracelet creators are also adept at pattern interpretation– e.g., identifying sub-patterns that inform an efficient and regular order of operation for manual pattern execution. With Knotation, we focused on pattern drafting. However, our results suggest opportunities for future work in guiding creators in interpretation as well. Motifs already provide a repeating organizational structure within a complex pattern. We noticed in the workshop that first-time bracelet fabricators relied on a naive fabrication approach of reading the motif horizontally row-by-row– a process that requires extensive cognitive effort to track which knots have been executed. An alternative approach would be to use Knotation to identify and highlight diagonal knot segments within a motif and indicate a pattern of execution. This approach could guide the user through an efficient fabrication method for a given design, while also helping them develop an understanding of general segmentation and fabrication strategies.

B. Benefits of Parametric Design for Macramé Production

We found clear benefits to providing participants with a small set of parameters to manipulate motif-level pattern features. Because motif modules automate knot sequence generation and updates according to parameter changes, Knotation allowed participants to focus on aesthetics and design iterations rather than individual knot structure. Modifiers, in combination with motif modules, enabled participants to diversify their bracelet design through parameterized, pattern-level modifications. Each pattern created by our participants during the workshop was unique and personalized. Despite limitations in current modifier functionalities, participants found them useful and saw many opportunities to expand modifier features. Furthermore, they produced a large number of design outcomes in a short period of time.

Our results suggest that Knotation can also support unique design insights. As we established in Section II-C, the existing pattern drafting workflow involves first drawing a sketch and then using a digital pattern generator to execute it. This workflow is a poor fit for creators who lack prior knowledge of the design process and, therefore, cannot envision pre-planned designs. Knotation enables an alternative workflow that prioritizes experimentation. Most participants formulated their designs by exploring the effects of applying different modifier modules rather than executing a pre-planned pattern. Participants would notice intriguing aspects start to appear in their pattern after applying certain modifications and then decide if they'd move forward with that aesthetic direction. Similarly, our own example pattern, *Variegated Diamond* (described in Section III-G), was created with some degree of experimentation. We discovered we could create a triangle-checkered effect while testing the Modify Row module. These observations suggest that the experimental workflow of Knotation facilitates design ideation and provides design inspiration. Achieving similar design workflows through non-parametric friendship bracelet design tools would be difficult because they work at knot-level edits, making the cost of experimentation much greater. In contrast, Knotation enables rapid edits with low effort, which allows for open-ended design discovery. Additionally, Knotation provides a solution to integrate exploration and targeted design by enabling the user to export their design in a format compatible with the existing BraceletBook.com pattern generator for knot-level pattern refinement.

C. Improving the Usability of Macramé Parametric Design

Workshop participants were able to produce a wide range of outcomes with motifs and modifiers alone; however, the expressiveness of Knotation could be expanded by enabling users to combine multiple motifs in the same pattern. By introducing a merge function to connect multiple motifs, we could extend Knotation's capability to support drafting different pattern dataflows in parallel. Concatenation can be achieved by joining patterns vertically or horizontally; however, there are a few caveats to consider in implementing such a feature going forward. The first relates to thread count. When concatenating different patterns, their dimension compatibility may conflict with fabrication constraints. For example, if we were to vertically concatenate two patterns with different thread counts, we would need to reconcile different pattern widths. We could achieve this by either discarding parts of the wider pattern or by accepting loose threads in the bracelet design. Loose threads are aesthetically undesirable, and it takes a higher degree of manual skill to conceal them. Alternatively, we could impose a constraint to only allow patterns with matching lengths or widths to be concatenated. This would reduce the flexibility of the design process but ensure consistent aesthetic output during fabrication.

The second caveat relates to the geometry of the motif itself. Geometry boundaries of patterns, defined by populated elements in their array representations in Knotation or physically by their underlying knot sequences, are rarely tileable. Unless their joining edges are of complementary shapes, two patterns cannot be seamlessly joined. To resolve this, we could enact a naive approach by simply concatenating both patterns' array representations; however, this approach would result in large gaps between patterns. Such structures are possible to fabricate, but aesthetically undesirable. Another option could be to algorithmically join patterns so that gaps are minimized. A general approach for joining two patterns vertically would be as follows: we could start by identifying the lower boundary of the first pattern. Then, we could identify the top boundary of the second pattern and any empty space above it, which acts as an overlap zone. To merge the pattern arrays, we could overlap rows between the patterns to eliminate the overlap zone as much as possible until boundary knots become neighbors. Alternatively, we could enable the user to control the amount of separation or overlap between concatenated patterns. However, it would require more manual design effort.

We developed the original Knotation system to support parametric control while retaining designer agency. The inclusion of more extensive design automation should be evaluated with regard to the degree of control desired by the target audience. Extensive automated concatenation of patterns may be undesirable to designers if it reduces control of the aesthetic or produces sub-par functional properties during construction.

VI. Conclusion

By identifying the alignment of parametric design and macramé, we developed Knotation, a parametric dataflow tool for friendship bracelet craft. We identify a new opportunity space for parametric craft that extends computational textile research. Our approach successfully enables a high degree of design exploration and iteration among newcomers and suggests future opportunities for extending the dataflow paradigm to scaffold the transition from digital parametric design to physical fabrication.

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