Foundations for 3D Machine Knitting

Vidya Narayananan
Why Machine Knitting?

Shima Seiki

Bosch

Koerbner et al.

Stoll

Zaha Hadid/ETHZ

Ford

Shima Seiki/Ryukoku Univ

Existical

Addict

Valve

Knit-Rite
Fabric constructed using a single yarn by forming loops and intermeshing them.
Knitting machines are programmable systems made of needles that can manipulate yarn into knit structures.
Programming knitting machines is hard

Design space is not well specified, no unified pattern representation
Programming for machine knitting can be organized to decouple high-level design from low-level machine input.
Decouple “what” and “how”

**What**
- Design model with CAD tools
- Interactively pick tool and region for tool path

**How**
- Geometric tools for optimizing shape and support

**CNC-Milling**
- GCode

**3D Printing**
- GCode

**Domain Specific Programming**
- DSL program for high-level task

**Examples**
- **CNC-Milling GCode**
  ```
  mov eax, [ebp+8]
  mov esi, [ebp+12]
  mov edi, [ebp+16]
  add [ebp+4], esi
  x86/64
  ```

- **3D Printing GCode**
  ```
  mov eax, [ebp+8]
  mov esi, [ebp+12]
  mov edi, [ebp+16]
  add [ebp+4], esi
  x86/64
  ```

- **Domain Specific Programming**
  ```
  mov eax, [ebp+8]
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  add [ebp+4], esi
  x86/64
  ```
Decouple “what” and “how”

What

How

Low-level Operations

Shape 3D Model
<table>
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<tr>
<th>What</th>
<th>Key Questions</th>
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</thead>
<tbody>
<tr>
<td>What can be machine knit?</td>
<td>What makes a good pattern representation?</td>
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| How                       | How do we convert 3D models to patterns? | How do we generate low-level code? |
Proposed work

What

What can be machine knit?
Generalize 2-bed machines to multi-layered machine

What makes a good pattern representation?

- Transfer-free remeshing
- Interactive Bed-view
- Hinted Scheduling
- Topological Edits

How

How do we convert 3D models to patterns?

How do we generate low-level code?
# Key Questions

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What can needles make?

- Needles hold loops
- Needles can “grab” yarn and pull new loops through old loops
- Storage is temporary
Arrangements of needles

What can be made?

- Linear (Single bed)
- Circular
- Two-bed

What representations?

- 3D Model to Pattern
- Pattern to Code
Operations on a linear machine

What can be made?
What representations?

3D Model to Pattern
Pattern to Code
Operations on a linear machine

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
What can linear machines make?

Yarn path might be complex, but the surface is “sheet-like”
What can linear machines make?

Yarn path might be complex, but the surface is “sheet-like”
Arrangements of needles

What can be made?

- "sheets"
- "tubes" and sheets

What representations?

- 3D Model to Pattern
- Pattern to Code
Linear “two-bed” machines

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Move loops around to widen and narrow

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Translate and rotate active loops

A Compiler for 3D Machine Knitting

What can be made? | What representations? | 3D Model to Pattern | Pattern to Code
What can two-bed machines make?

Multiple tubes of different shapes

Tubes can split and merge

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Top view

Tubes cannot be reordered with two layers
Tubes can be reordered with four layers
Emulating a multi-layer machine

Generalize 2-bed machines to multi-layered machine

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
Emulating a multi-layer machine

What can be made?

What representations?

3D Model to Pattern

Pattern to Code

Yarn tangling!
Shuffle layers around to make space

Separate layers

Work on “current” layer

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
Emulating a multi-layer machine

A **layer** is a sequence of needles on *both* the front and back bed. For any index, only one bed location is occupied at any time.
Interleave layers for emulating a multi-layer machine

A two-bed knitting machine can be used to emulate finitely many layers.
Constructing a surface on the machine

1. Time function
2. Contract contours
3. Reeb graph skeleton
How many layers?

Events on the (projected) graph

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
How many layers?

2 layers
How many layers?

4 layers

What can be made? 

What representations? 

3D Model to Pattern 

Pattern to Code
Given a time function with an upward graph, an oriented manifold can be knit on a 4-layer knitting machine that makes infinitesimally small stitches.
Knittability of surfaces

Planar graphs

- Minimum (Birth)
- Saddle (Split)
- Saddle (Merge)
- Maximum (Death)
- Crossing (Right)
- Crossing (Left)

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Knittability of surfaces

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Knittability of surfaces

What can be made? | What representations? | 3D Model to Pattern | Pattern to Code
--- | --- | --- | ---
2 | 2 | 2 | 4
Knittability of non-manifold surfaces

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Knittability of non-manifold surfaces

Handling imbalanced curves with layers

4 layers

pleated skirt

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
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<tr>
<td><img src="image1" alt="Images of machine knit items" /> <img src="image2" alt="Images of machine knit items" /> <img src="image3" alt="Images of machine knit items" /> <img src="image4" alt="Images of machine knit items" /></td>
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<td><img src="image7" alt="Images of low-level code generation" /></td>
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Knitting design as programming

Yarn carrier and direction

Needle location

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
Knitting design as programming

Yarn carrier and direction
(Green)  (+/right)

Needle location (N1)

Code:
knit + N1 Green

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Knitting design as programming

Needle location
(N1) (N2) (N3) (N4)

Yarn carrier and direction
(Green) (+/right)

Code:
- knit + N1 Green
- knit + N2 Green
- knit + N3 Green
- knit + N4 Green

xfer N1 N2
rack amt
yarn-in Y
...

Knitout Specification [McCann '17]
Low-level representations are complete but not independent

"Knitout":

needle ops:
- tuck
- knit
- xfer

state ops:
- rack
- tension

yarn ops:
- in
- out

What can be made?

What representations?

3D Model to Pattern

Pattern to Code

Shima Seiki SDS KnitPaint  Stoll M1 Plus
Construction space primitives can be difficult to edit and may not be complete

Instructions:

needle ops:
tuck
knit
xfer

state ops:
rack
tension

yarn ops:
in
out

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Can we use 3D representations for machine knitting patterns?

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Edge-matching based stitch meshes

Stitch Meshes [Yuksel et al. ’12]
Knittable Stitch Meshes [Wu et al. ’18]
Encoding dependencies with edge directions

Only directed acyclic stitch meshes are valid.

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Encoding face programs for construction

Stitch Mesh + Directions

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Layer programs to bed programs

Transfer \([l+1, L-1]\) to back
Transfer \([0, l]\) to front
Kick forward active yarns
\(N = NL + l\)
Knit + fN Y

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Augmented Stitch meshes for machine knittable structures

Stitch Mesh + Edge Directions + Face Programs + Layers = Augmented Stitch Mesh

Visual Knitting Machine Programming [Narayanan and Wu et al. (2019).]
Only a small library of face programs needed

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Edge labels provide a function signature for face programs

A layer can perform both front and back operations
Edge labels provide a function signature for face programs

Fair-Isle

Fair-Isle1(N, Y)

\text{Fair-Isle2}(N, Y)

Plating

Plating1(N, Y)

\text{Plating2}(N, Y)

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Editing in the output space, intuitively

~[Peng et al. 13] connectivity editing

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Editing in the output space, intuitively

Introducing topological edits
What can be made?  
What representations?  
3D Model to Pattern  
Pattern to Code
Key Questions

What can be machine knit?

What makes a good pattern representation?

How do we convert 3D models to patterns?

How do we generate low-level code?
Augmented stitch meshes look like quad meshes

State of the art in Quad Meshing
Bommes et al. [2013]
Using quad-meshing algorithms for stitch mesh generation

- Edges can be directed and labelled consistently
- Shape matches (under some reasonable distance)
  - Faces match stitch shape, overall geometry matches
- Local machine code

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Incremental Remeshing

Automatic machine knitting of 3D meshes. [Narayanan et al. 2018]

Hierarchical Remeshing

Segment

Remesh

Refine

Visual Knitting Machine Programming [Narayanan and Wu et al. (2019).]

What can be made? What representations? 3D Model to Pattern  Pattern to Code
Incremental Remeshing

Knitting time ~1 hour
Patterning time ~0.4 hours

What can be made? What representations? 3D Model to Pattern Pattern to Code
Can we create patterns without transfers?

Transfer-free patterns are faster to fabricate, more gentle on yarns

2. Transfer-free knitting patterns
Shaping with short-rows

What can be made?  What representations?  3D Model to Pattern  Pattern to Code

Short-rows
A single layer machine cuts and glues along one axis

A cut can be “glued” if its angle bisector is orthogonal to the spine

Flattening = unfold along the shortest path to the spine,

Paths are “ordered” along the spine
Ordering paths on a surface

Shortest paths to the spine on a surface can be ordered.

Convex shapes

What can be made? | What representations? | 3D Model to Pattern | Pattern to Code
What can be made?

Exact geodesic distances [Surazhsky et al. 2005]

Uniformly sample points and compute shortest paths

Create density map

Accumulate pixels

Improve discretization

3D Model to Pattern
Constructing the unfolding by cutting

Exact geodesic distances
[Surazhsky et al. 2005]

Explicitly computing the cuts can be numerically unstable

Intrinsic Triangulations
[Sharp et al. 2019]
Generating a stitch mesh structure

Knitting

Weaving

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
Key Questions

What can be machine knit?

What makes a good pattern representation?

How do we convert 3D models to patterns?

How do we generate low-level code?
Scheduling augmented stitch meshes

Allocate needles

Generate Code

What can be made?
What representations?
3D Model to Pattern
Pattern to Code
Planar Case: Enumerate layouts for critical rows

Enumeration layouts of critical rows (starts, ends, splits, merges)

Automatic Machine Knitting of 3D Meshes [Narayanan et al. (2019).]

What can be made?  What representations?  3D Model to Pattern  Pattern to Code
Limited number of layout shapes are evaluated

Limited number of layout shapes are evaluated

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
Minimize intermediate transfers

Embedding

Minimize rotation, translation

What can be made?

What representations?

3D Model to Pattern

Pattern to Code
General Case: User assigns layers and resource hints

Resource hints  Assign Layers
Additional temporal dependencies

Loops agree on connections.
Yarns may disagree on connections.
A topologically valid schedule

- tuck + f0 A
- tuck + f2 A
- knit – f2 A
- knit – f0 A

Diagram:
- Back-bed track
- Front-bed track
- Yarn track
What is a valid schedule?

• Length of yarn between loops (slack) is exactly as prescribed during construction.
• Slack is at most the prescribed value after construction.
• Topologically equivalent to the initial schedule.
Rules to conservatively edit the graph

R1: Conjugate loop operation with transfers
R2: Insert/Remove paired transfers
R3: Re-order independent instructions
Rules to conservatively edit the graph

User-guided scheduling
Key Questions

What
What can be machine knit?

What makes a good pattern representation?

How
How do we convert 3D models to patterns?

How do we generate low-level code?
Key Contributions

What

What can be machine knit?
Design Space
Layer-based machine model

What makes a good pattern representation?
Augmented Stitch Mesh

How

Field-aligned Remeshing
Unfolding with cuts

How do we convert 3D models to patterns?

Automatic tube scheduling,
Interactive user-guided general scheduling

How do we generate low-level code?
A better ecosystem for machine knitting!
A better ecosystem for machine knitting!

- Customized geometry
- Long and accessible zippers
- Away from contact
- Smooth texture

2-4 design iterations

2 prototypes
Design for function, domains and devices

- Furniture for accessibility
- Packaging for modular shipping
- Supports for house plants
- Mosquito blocking clothing
- Fashion, Medicine, Architecture…

Domain-specific, Data-driven tools

Fit
Comfort
Support
…

Functionality

3D Design Tools

Shape

Interaction

Design

Memomi
Most real-world objects are not made of one material or a single fabrication technique.
Optimization for hardware, optimizing hardware
- Novel applications in design and engineering
- Cater to local, on-demand production

Diagram:

- 3D Design Tools
- Yarn Simulation, Material Libraries
- Pattern Datasets
- Machine-Independent Specification
- Compile & Optimize
Lea Albaugh, Kui Wu, Jenny Lin, Jianzhe Gu, Michelle Guo, Lining Yao, Cem Yuksel, Stelian Coros, Ella Moore, April Grow, Jen Mankoff, Yuka Ikarashi, Gilbert Bernstein, Jonathan Regan-Kelley, David Breen, Team Shima Seiki

Thank You!