Personalized Knit Masks

Programmable Shape Change for Customized Fit

Lavender Tessmer
Massachusetts
Institute of Technology

Skylar Tibbits
Massachusetts
Institute of Technology

1

1 Knit fabric with zones of temperature-responsive fibers (left); knit mask, before and after the personalized robotic tailoring process (right).

ABSTRACT

In this paper we outline a new workflow for textiles customization through the design and fabrication of knit shape-changing masks that contain multi-material fibers to create programmable transformation. We have created a process for producing standardized and scalable textile goods using a flatbed industrial CNC knitting machine which are then "tailored" to an individual's body measurements through a system of programmable textiles, custom multi-material fiber, and robotic heat activation. Hybridizing the efficiency of standardized textile production with unique geometric variation, the proposed strategy centers on the shape-change behavior of fibers and precise knit structures to produce personalized textiles. This work focuses on the face mask as an example of a now-ubiquitous textile good that is often ill fitting and yet can now be highly tailored to an individual's personal fit and comfort. This paper outlines the materials, knit fabric development, mask design, digital workflow, and fabrication steps for producing truly customized masks for an individual's unique facial geometry.

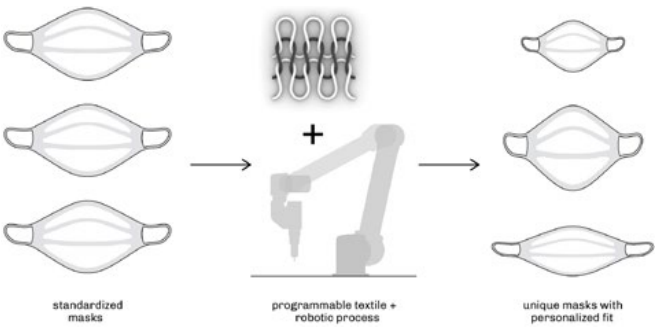
INTRODUCTION

Mass-customization often comes at the expense of scalability and efficiency. Existing workflows for mass customization often rely on design-to-machine processes to produce parts that are geometrically unique, resulting in increased complexity. A customized production approach is especially relevant in the apparel industry offering the potential for better fit, more comfortable, and more individualized clothing. In particular, industrial knitting machines have significant potential as a production tool for customizable garments due to the highly reconfigurable CNC control of fabric shapes and patterns. However, there are significant challenges for producing on-demand customized knit geometries that relate to the complexity of material behavior and digital workflows for machine output.

Current explorations in mass-customized garments and accessories in the apparel industry have focused almost exclusively on producing customizable garment patterns in software that can be sent directly to a textile machine or garment construction process (Apeagyei and Otieno 2007). With a similar strategy, computer scientists have made progress in developing these automated workflows for on-demand production of knit geometries, but these approaches often acknowledge numerous barriers to realizing a scalable and seamless process for generating unique and dimensionally accurate pattern shapes (Narayanan et al. 2018; Wu, Swan, and Yuksel 2019). This software-based approach to customization has significant challenges due to the low dimensional stability of knit fabric, the inability of the automated process to adapt to the nuances of material, the difficulty of predicting the behavior of a textile as well as the interaction of forces applied during knitting and its effect on the final geometry.

This paper explores a new process for garment customization that does not rely solely on software-based pattern generation, and instead focuses on material properties and tailored activation, demonstrating an alternative workflow for customization and production. Balancing repeatability with the potential for variety, the proposed solution leverages the efficiency of scalable garment production using industrial knitting machines coupled with programmable material fibers to produce fully customized objects through temperature activation (Figure 1a). To test this process, we have fabricated a set of standardized knit masks that are pre-programed with the ability to change shape for a personalized fit (Figure 1b). The customization of fit is achieved using heat postprocessing with a robotic toolpath that is translated from each wearer's individualized face measurements (Figure 2). This approach allows for the full speed and efficiency of industrial knitting machines and standardized files which are widely used in the apparel industry total, while still enabling a fully tailored and personalized textile product through a post-process material transformation.

As many people adapt to the new and widespread wearable accessory of face masks, it has become clear that masks often do not fit correctly or cannot accommodate the wide range of face sizes and shapes. Often ill-fitting and uncomfortable, mass-produced mask designs highlight a forced standardization in contrast to the diversity of individual human shape and proportion. Our approach to creating shape-changing customized masks presents a unique opportunity to develop and evaluate new methods of producing personalized items.



2

2 Concept: robotic process and programmable textile are used to transform standardized masks into personalized masks.

This project builds on previous research in the Self-Assembly Lab at the Massachusetts Institute of Technology. This work includes 4D printing which uses contrasting material properties along with intricate 3-dimensional geometry to promote precise shape-transformation in a printed part when subjected to moisture (Papadopoulou, Laucks, and Tibbits 2017). More recent work translates these strategies to textiles, demonstrating a proof of concept for a heat-activated "robotic tailoring" technique for a multi-material knit sweater and a climate-adaptive garment that changes porosity and thickness based on the environment (Tessmer et al. 2019). Continuing this research, this project aims to further develop the earlier projects with a new computational workflow to link personal fit measurements to precise shape change and transformation.

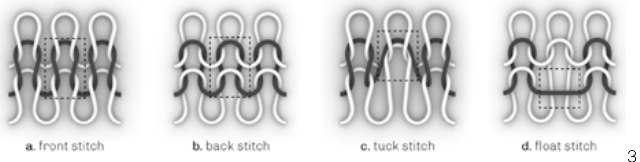
BACKGROUND

This work aims to synthesize a number of different research areas into a novel strategy that combines apparel design, knit fabric, custom-made fibers, mask design, and robotic fabrication. Among these areas are manufacturing workflows for mass-customizable garments, industrial knitting, the behavior of knit structures, material research in heat-responsive fibers, fabric heat-setting techniques, and customizable robotic toolpaths.

In the area of fashion apparel, researchers have identified methods of evaluating fit variables for customized garments, as well as verified consumer desire for personalized fit (Bellemare 2018). Other work in this area has established a production process that works between customer size data, garment design, and knitting production. Through this work, researchers have identified a need for addressing the dimensional stability of knit fabrics in the custom-manufacturing workflow by incorporating a thermosetting process that adapts to the dimensions of the individual input data (Buecher et al. 2018). Likewise, our workflow incorporates a heat post-processing technique with individual size data and industrial flat-bed knitting. However, we expand on this approach by introducing a heat setting process that incorporates multi-material fibers and an individualized heat application.

Among the methods of industrial textile production which include weaving, braiding, and others, knitting offers key advantages for leveraging the small-scale configuration of fibers to generate large-scale behaviors in fabric. Knit fabrics can integrate stitch-by-stitch material changes and fiber configurations. Furthermore, local properties at the scale of a single stitch can accumulate into overall behaviors in larger zones of fabric. Conventional flat-bed industrial knitting provides numerous ways to arrange multiple materials in small areas on the face and the cross section of the fabric. Industrial knitting is a scalable and widespread manufacturing process used to produce a wide range of items which includes garments, accessories, and shoes.

Knit fabrics are composed of rows of interlocking loops formed by needle mechanisms in the knitting machine (Spencer 2001). Each needle can perform a set of different actions that result in different loop types, programmed as a set of symbols. Common types of needle actions include front stitch, back stitch, tuck, and float (Figure 3). "Knit structure" refers to the pattern in which these stitch types are combined and deployed in the overall fabrics. The knit structure has a significant effect on the overall behavior of the fabric, including its appearance, texture, and ability to stretch, and in this case can serve to constrain the direction of shape transformation in the textile.



3

There are a number of examples of existing knitting research that apply knit structure to achieve fabric behaviors for different applications and functions. In architecture and design, existing projects have utilized knit structure to manipulate fabric to produce folding, actuation, and variation in elasticity with a wide range of effects (Ahlquist and Menges 2013; Baranovskaya 2016; Scott 2013; Pavko-Čuden and Rant 2017). In engineering, researchers have combined knit structure with shape memory materials to produce curling mechanisms and to adapt to the shape and motion of the human body (Abel, Luntz, and Brei 2013; Eschen et al. 2018). Our proposed approach uses both knit structure in combination with custom-made multi-material fibers and a robotic activation process to control shape change in fabric.

To produce fabric transformation, this project employs various heat responsive "active" fibers. This includes a shrinkage force and a bulking behavior using a thermoplastic fiber and a bicomponent fiber. Thermoplastic fiber shrinkage in knit fabrics is well-documented, and is characterized in its effect on washing, drying, or manufacturing of knit fabrics and garments (H. A. A. E. Perera and Lanarolle 2020). Bicomponent fibers combine two materials with contrasting properties that are extruded and fused together in cross section. These fibers typically produce a curling behavior in response to a moisture or heat stimulus that affects the texture of the fabric (Rwei, Lin, and Su 2005; Prahsarn et al. 2013). In this project, we leverage these fiber properties as a feature for controlling shape change, utilizing a combination of both types of fiber behaviors in response to heat.

Heat setting is a widely used technique in industrial textile production. It can be used to improve dimensional stability of knit garments, or to produce interesting textural effects (Haar 2011; A. E. Perera, Lanarolle, and Jayasundara 2019). Our technique expands the role and purpose of heat setting, applying a unique and precise process to achieve full shape customization for individual masks.

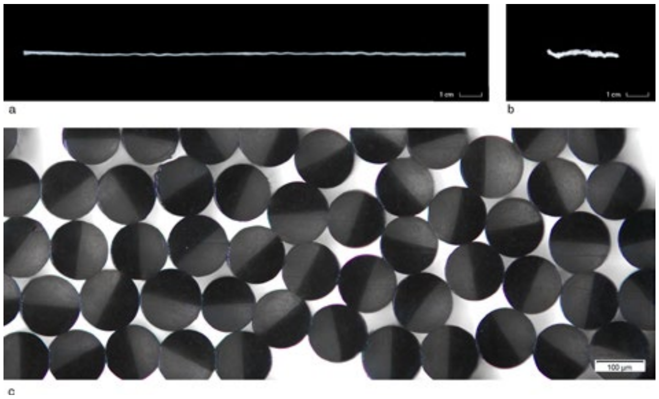
Finally, robotic toolpaths for customization and repeatability have been extensively used in architectural research (Gramazio, Kohler, and Willmann 2014). Particularly relevant are the robotic means of transforming standardized material into geometrically differentiated objects in response to input data. Our strategy virtualizes the connection between unique instances of input data and the customized outcome, performed here by the interaction between precise application of heat (based on an individual's facial measurements) with the active fiber material and programmed knit fabrics.

METHOD

Our approach to creating customized knit textiles involves several steps: the selection of active and inactive materials; the integration of these materials into knit structures that are able to transform directionally; the characterization of the directional fabrics' shape change relative to the robotic parameters; the design of a mask that integrates different knit structures to accommodate unique face shapes, and a computational workflow that generates a robotic tool path for tailoring the mask to a specific individual's measurements.

Materials

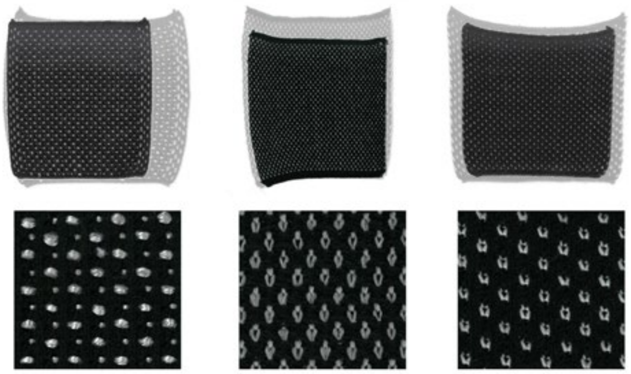
The knit fabric of the mask contains a combination of inactive and active materials. The first active material, Grilon K85, is a thermoplastic fiber that exhibits a contracting force when heated to a temperature range of 95 - 120C. Grilon is a self-fusing polyamide copolymer that is commonly used in industrial textile settings, often to create fused seams and edges (EMS-CHEMIE Holding AG 2021). The material has a high linear contraction in response to heat (Figure 4a, Figure 4b). Each of the knit structures within the mask utilizes two strands of 380-denier Grilon K85 (760 denier total). Grilon is plied with one strand of a second active material: a custom-made 72-filament bicomponent fiber which contains two materials: linear low-density polyethylene (LLDPE) and polyamide-6 (PA6) in its cross section (Figure 4c). When both types of active fiber are heated together in the fabric surface, it produces a permanent, heat-sensitive contraction with a soft surface texture. In the knit fabric, the active fibers work together with an "inactive" synthetic staple yarn which consists of 72% Viscose and 28% Polyester. Small amounts of a synthetic elastic yarn are used in the mask's periphery, forming the edges and ear loops.



4

Knit Structures

Linear contraction of the active fibers can be transferred to directional contraction in the fabric through the configuration of two materials together in a knit structure. Using these materials, we develop a set of knit structures where the inactive material serves to elongate non-looping lengths of active material. By inserting different patterns of active material into the inactive material, it is possible to control the direction of dimensional change in an area of the fabric. We employ three transforming knit structures in the mask, each with a different directional behavior: weft inlay to produce vertical contraction, held stitches to produce vertical contraction, and diagonal floats to produce diagonal contraction (Figure 5a, Figure 5b, Figure 5c). In each case, the active material forms a directional pattern within the inactive material, influencing the physical transformation. These structures are designed with symmetry on the front and back fabric faces to limit unwanted curling during the heating process, as well as sufficient thickness to feel durable and protective.



5

3 Examples of knit stitch types, showing basic interlocking loop structures (a, b) and non-loop-forming stitches (c, d).

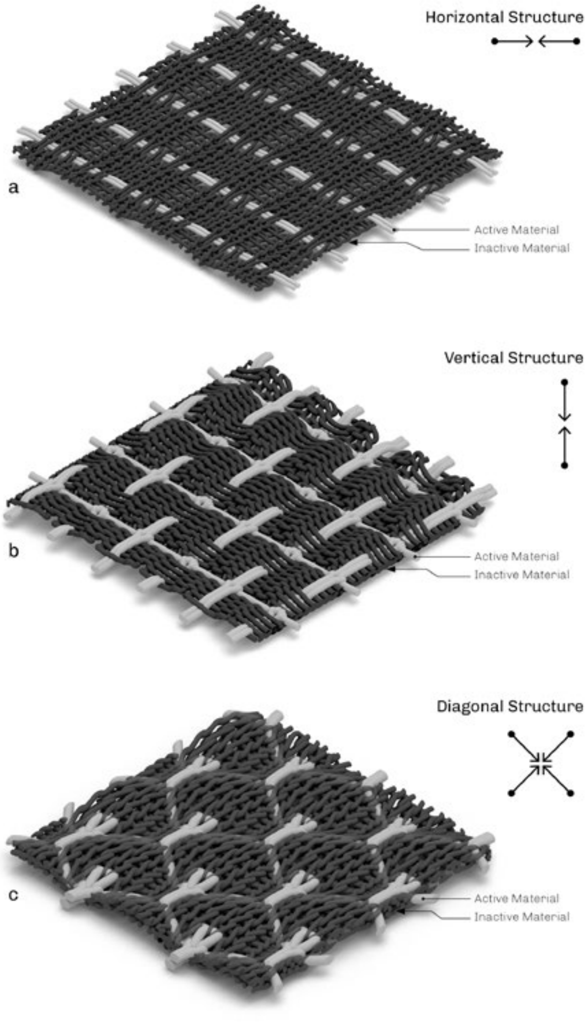
4 Thermoplastic shrinkage of Grilon fiber before (a) and after (b) exposure to 95-120C temperature range; cross section of bicomponent fibers containing LLDPE and PA6 (c).

5 Detail of knit structures with horizontal (left), vertical (center), and diagonal (right) behaviors, showing overall fabric contraction after heating.

Three Stitch Patterns of Active Fiber

1) Horizontal contraction: A weft inlay is a method of inserting a continuous fiber into a horizontal course of stitches; the inserted fiber does not form loops and maintains an entirely width-wise orientation. When an active fiber is placed as the inlay material, the result is a horizontal contraction of the entire fabric surface with very minimal change in the vertical direction (Figure 6a).

2) Vertical contraction: Our strategy for generating a proportionally higher vertical contraction is to drastically elongate the loops of front stitches following an alternating pattern. This results in a predominantly lengthwise orientation of uninterrupted linear active fiber. When the fabric is heated, the longer stitches of active material contract predominantly in a lengthwise direction (Figure 6b).

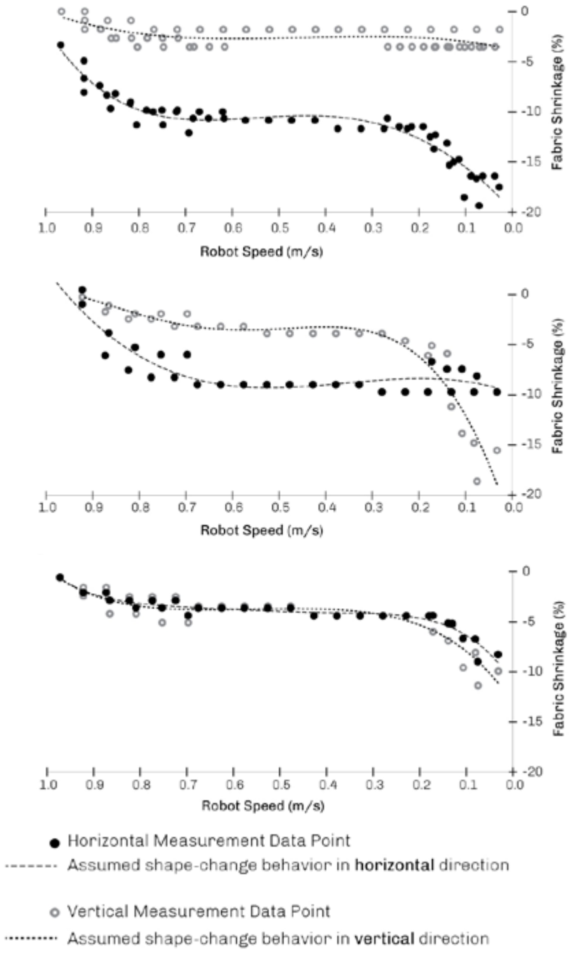


6 Illustration of the active and inactive fiber locations in each of the three transforming knit structures.

3) Diagonal contraction: The third strategy for producing controlled dimensional change in knit fabric is through the placement of diagonal floats. This results in a secondary network of active fibers that pull the fabric inwards in both directions. Since the floats are oriented diagonally in two directions, the horizontal-to-vertical proportion of contraction is relatively even compared to the previous strategies (Figure 6c).

Robotic Heat Application and Shape Change

To test how each of the knit structures behaves when heated, a heat gun with a 5mm nozzle was mounted to a 6-axis robotic arm and was used to apply heat to a set of fabric samples following precise toolpaths. The temperature of the heat gun was set at 137C and was stepped across the fabric in 2mm increments, traveling 12mm from the fabric surface. The sample was fixed to the table surface and covered with a wire mesh screen to prevent



7 Characterization of horizontal (top), vertical (middle), and diagonal (bottom) ,active knit structures with robot speed and size measurement data. The measurements show that slower robot speeds correlate to increased transformation of the fabric; each knit structure exhibits a different shrinkage behavior in the horizontal and vertical directions.

unwanted motion of the fabric in the vertical axis. After each full pass of the robot, the horizontal and vertical size of each sample was measured and recorded. The speed of the robot was varied during each test which exposed the fabric to different durations of heat; all other parameters remained the same. After tests were conducted on a range of different robot speeds, the measurement data was recorded to establish a predictable relationship between robot speed and percentage of shrinkage. The tests demonstrate three differing shrinkage behaviors corresponding to each knit structure which informs the design of the mask (Figure 7).

Mask Design and Fabrication

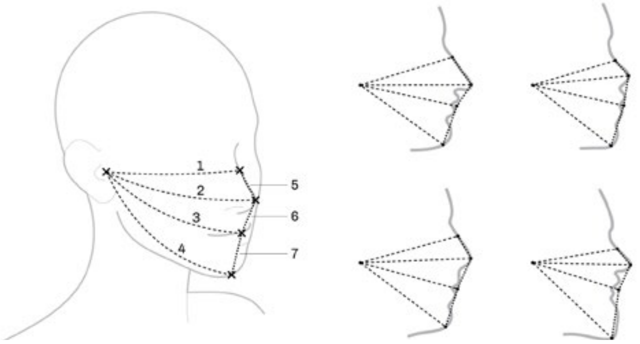
Standardized, mass-produced masks are typically available in different size gradations (S, M, L, etc.) or contain built-in strategies such as elasticity, adjustability, or expandability for adapting to multiple face sizes or shapes. Many of these mask designs inherently exclude certain face shapes or apply a single presumed set of facial proportions across a set of standardized sizes. As an alternative to this, the proposed strategy uses a self-measurement system that can record facial differences and embed them in the design of the mask to actively morph to the unique geometry of someone's face, through the strategic placement of active material and knit structures. The mask design is based on seven facial measurements that seek to identify the key dimensional relationships and proportions with facial features including the nose, mouth, chin, and ear (Figure 8):

Horizontal face measurements:

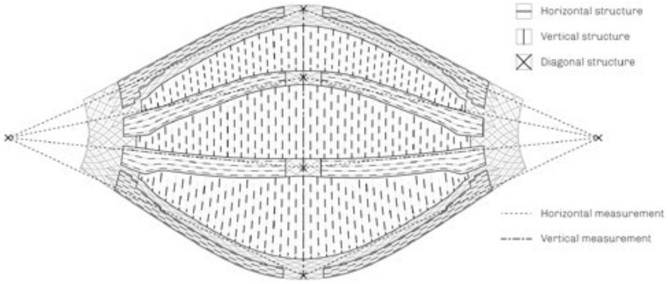
- 1: Nose bridge to ear
- 2: Nose tip to ear
- 3: Mouth to ear
- 4: Chin to ear

Vertical face measurements:

- 5: Nose bridge to nose tip
- 6: Nose tip to mouth
- 7: Mouth to chin



8



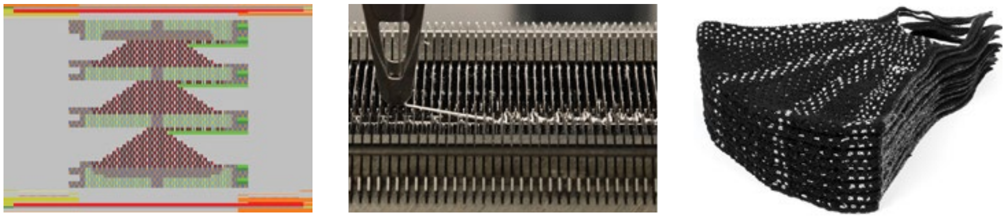
9

8 Location of seven facial measurements used to develop the mask design that can adapt to different facial sizes and proportions. The measurements are recorded as inputs to generate the geometry and corresponding speeds of the robotic tool path.

9 Mask design with layout of horizontal, vertical, and diagonal knit structure areas. Each area corresponds with a facial measurement location.

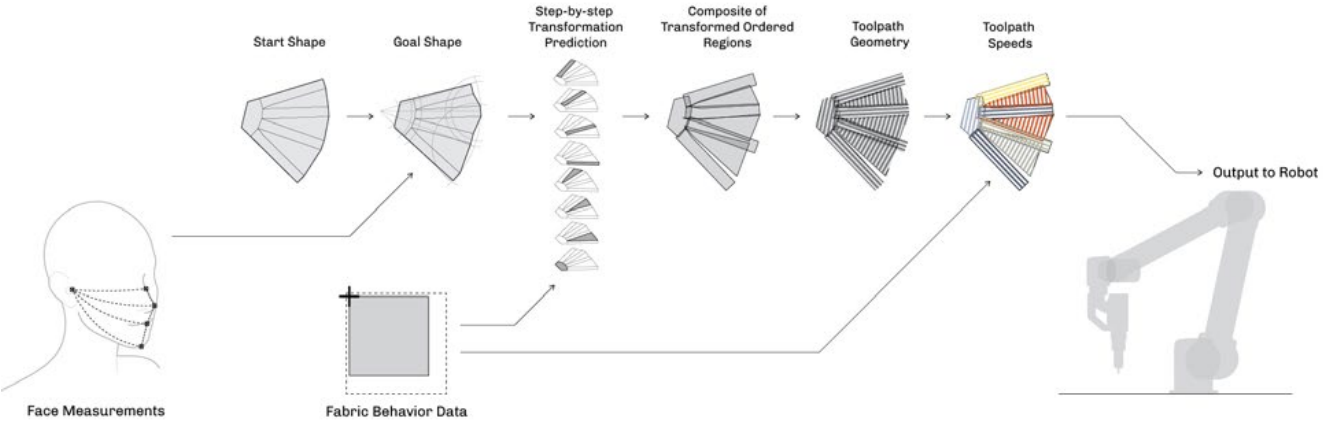
The measurement system acts as a scaffold for locating and organizing the three knit structures, and the regions of different fabric behaviors are applied as a tool for adjusting each of the seven input dimensions. The horizontally acting zones can adjust the size and relative proportions of the nose bridge, nose, mouth, and chin while the vertically acting areas can adjust the spacings between them. The regions with diagonal structures absorb the contrast between the vertical and horizontal areas while providing stability to the sides of the mask (Figure 9). The initial size of the mask is calibrated to encapsulate an approximate range of standard sizes from XS to L, enabling a maximum potential of 60mm of shape change for each of the horizontal regions and 40mm of total shape change for vertical regions.

The knit masks are produced on a STOLL CMS HP-W TT Sport Industrial knitting machine, which is programmed using the M1PLUS software interface (M1PLUS (version 7.2.037) 2021). After knitting, the masks are hand-washed once in cold water, folded in half, and dried flat (Figure 10).



10

10 Programming and production of masks on a STOLL CNC knitting machine.



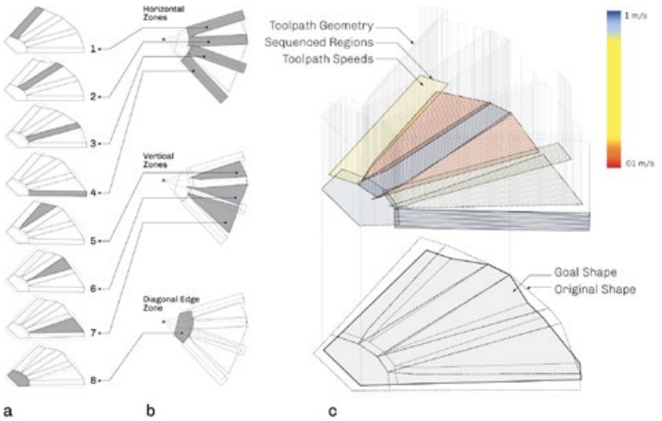
11 Digital workflow integrating facial measurements, fabric behavior data, and tool path output.

Toolpath Script

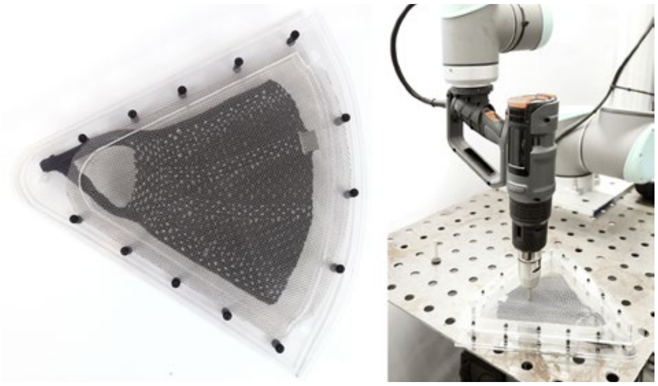
A script using Grasshopper 3d and the Scorpion plugin translates between the individual measurements and the standardized mask design to generate and output a robotic tool path with varied speeds that correspond to the necessary amount of shape change for each set of input measurements (Grasshopper 3d (version 1.0.0) 2018; (Scorpion (version 0.2) 2017)). In addition to producing the tool path, the script predicts the amount of shape change during the robotic process while the fabric moves and shrinks as it is being activated. Using the previous swatch testing measurements, the script builds an approximation of the original and transformed states and outputs the toolpath geometry with assigned speed parameters for the robot (Figure 11).

First, the geometry of the initial standardized shape is constructed and organized into a sequence of zones that corresponds to eight different areas of the mask. Each of the zones contains a single knit structure, the first seven of which correspond directly to the seven facial measurements. Zones one through four contain horizontal structures; zones five through seven contain vertically contracting structures, and the final zone contains the diagonally acting structure near the ear loops (Figure 12b). Next, the individual input measurements are used to construct the intended geometry of the finished mask; the difference is calculated between the initial mask size and measured inputs from the individual. Both the original and transformed representations of the mask are constructed using the same geometric “scaffold”, approximating both existing and potential conditions using measured behavior that is known about the three knit structures.

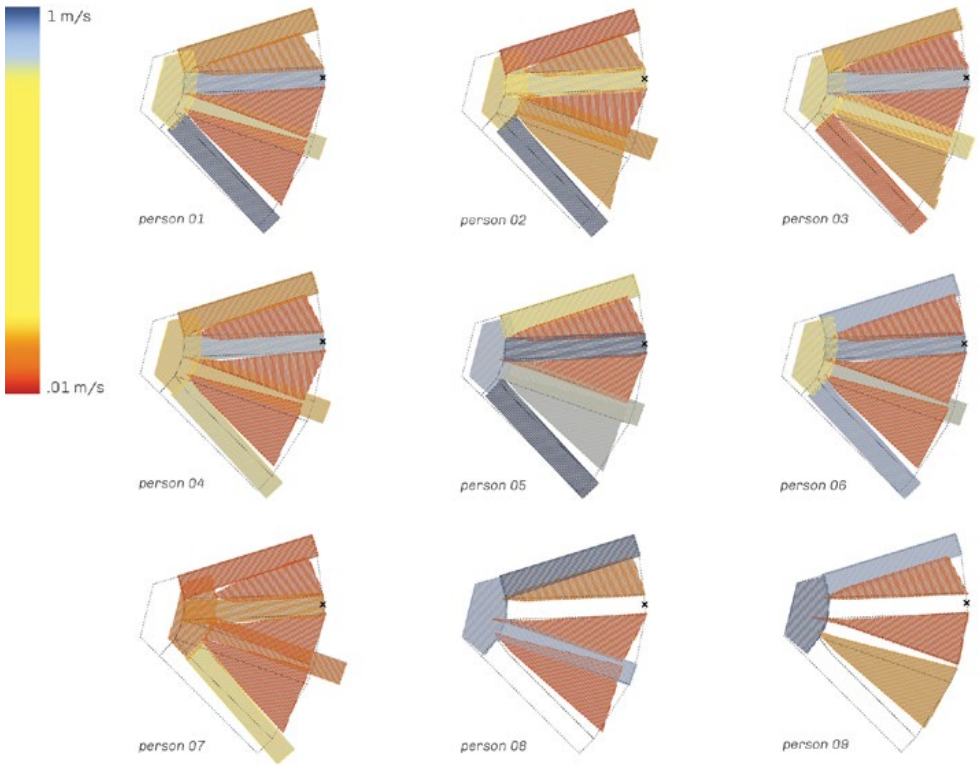
A composite of both sets of measurements is then assembled to estimate the zone-by-zone motion during heating, producing a series of geometries that represent each step of the mask’s shape during the heating process (Figure 12). Before an area is heated, it is represented by its initial shape and location; after it is heated, its size and location are updated into a transformed shape along with any zones that are affected by the change. The transformed shapes are generated using the measured data — represented as functions that describe the behavior of each knit structure — from the earlier swatch tests. A 2mm stepping tool path is then assigned to each zone, and a robot speed is determined based on the amount of intended transformation using the swatch test data (Figure 12c). If no transformation is necessary for a particular zone, it is omitted from the path.



12



13



14

12 Sequence and approximation of zone-by-zone transformation (a); areas of directional fabric transformation used to form a composite geometry (b); application of stepping tool path geometry and robotic speeds to the activation areas (c).

13 Mask-holding frame (left) and robotic heating setup (right).

14 Set of unique tool path geometries and robot speeds corresponding to the unique facial measurements of nine participants.

15 Examples of 2D scans of the original and transformed masks from three participants overlaid with facial measurement guidelines.

Robotic Activation

When heat is applied with the robot, the mask is affixed inside a holding device and anchored at a single point at the nose area. The holding device holds the mask in a precise location on the table surface and is covered on the front and back with a screen to prevent unwanted out-of-plane motion during heating (Figure 13). After the tool path is run once, the mask is flipped, and a mirrored version of the process is applied on the reverse side. The mask is then turned inside out, and the entire process is repeated so that both sides of fabric are exposed to heat.

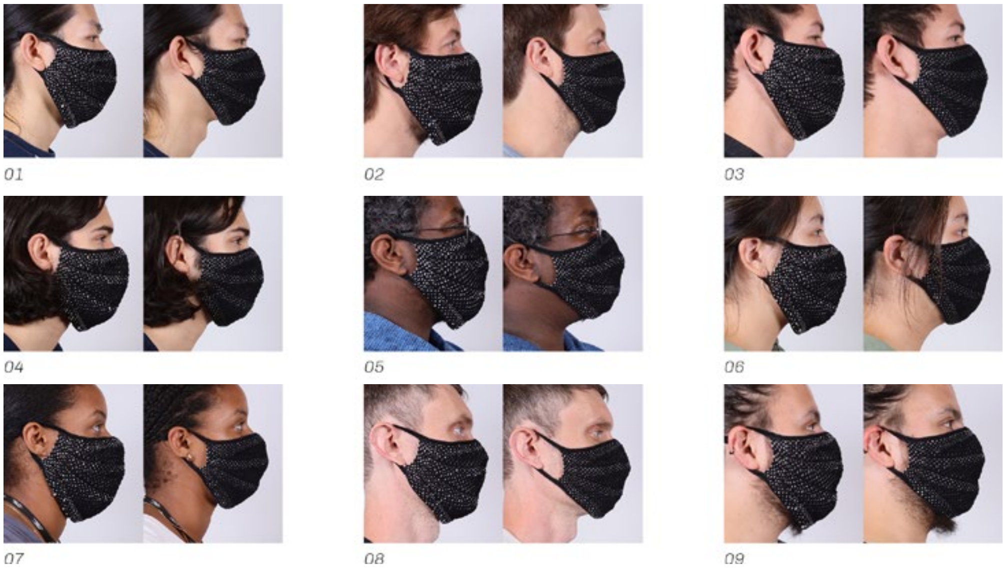
RESULTS

The proposed process was tested using the measurements of nine people. Each individual measured their own face, and a unique tool path was generated for each mask (Figure 14). The masks were evaluated by 2D scanning and comparing the original with an overlay of the transformed mask (Figure 15). To further test the fit of the masks, each individual was photographed wearing the mask before and after the heating process is performed (Figure 16).

This process resulted in the successful production of nine differentiated masks, and in every case the transformed fit was a significant improvement from the initial fit. The participants also reported that the masks were comfortable and fit much better than a standard mask, subjectively demonstrating effectiveness of the workflow. The masks were able to adapt to a wide range of face sizes and shapes represented by the participant group.

However, some aspects of the shape-change process were more successful than others and there are a number of challenges to overcome in future work. The vertically acting knit structure is limited by inherent constraints of weft knitting, but there could be ways to improve its effectiveness with further knit structure development. Many of the input measurements contained a concave condition where a person's mouth is located (visible in person 7 and 8 in Figure 17), and the mask design was unable to fully adapt; this is most likely due to surrounding forces in the fabric that were not present during the initial characterization of knit structures. During the robotic heating process, the flat activation method was successful in reducing complexity during heat application, but it introduced new limitations that constrained the amount of possible transformation. This could be reevaluated in future iterations by testing three-dimensional frameworks.

15



16 Before (left) and after (right) front views of standardized masks transformed into personalized masks for nine participants.

Since the sample size of unique individuals was small, there is the potential for a more comprehensive method of evaluating how much facial variation can be accommodated by the mask design. To address this, our future work aims to increase the amount of shrinkage to at least -30% from the current -20% to improve on the current 60mm maximum transformation of the mask. We also aim to improve the process of evaluating the success of the fit after the mask is activated to account for face motion and interaction with other facial accessories such as glasses.

CONCLUSION

Through the use of programmable material, this project demonstrates a new approach for creating mass customized textile products, enabling the transformation from scalable and standardized production into truly personalized products. This process aims to differentiate the manufacturing process from the customization tool, allowing for a scalable production method while also creating a streamlined method for personalization with the user. We have been able to achieve this through the careful design and integration of a computational workflow, customized multi-material fibers, precise knit structure and a robotic post-process activation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge support from the Advanced Functional Fabrics of America, Oye Ajewole and Gihan Amarasiriwardena (Ministry of Supply), Ziyue Wendy Wu, the MIT Department of Architecture, and Hills Inc.

REFERENCES

Abel, Julianna, Jonathan Luntz, and Diann Brei. 2013. “Hierarchical Architecture of Active Knits.” Smart Materials and Structures 22 (12): 125001.

Ahlquist, Sean, and Achim Menges. 2013. “Frameworks for Computational Design of Textile Micro-Architectures and Material Behavior in Forming Complex Force-Active Structures.” In ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-1-926724-22-5] Cambridge 24-26 October, 2013), Pp. 281-292. CUMINCAD.

Apeagyei, Phoebe R., and Rose Otieno. 2007. “Usability of Pattern Customising Technology in the Achievement and Testing of Fit for Mass Customisation.” Journal of Fashion Marketing and Management; Bradford 11 (3): 349–65.

Baranovskaya, Yuliya. 2016. “Knitflatable Architecture - Pneumatically Activated Preprogrammed Knitted Textiles.” In Herneoja, Aulikki; Toni Österlund and Piia Markkanen (Eds.), Complexity & Simplicity - Proceedings of the 34th ECAADe Conference - Volume 1, University of Oulu, Oulu, Finland, 22-26 August 2016, Pp. 571-580. CUMINCAD.

Bellemare, Jocelyn. 2018. “Fashion Apparel Industry 4.0 and Smart Mass Customization Approach for Clothing Product Design.” In Customization 4.0, edited by Stephan Hankammer, Kjeld Nielsen, Frank T. Piller, Günther Schuh, and Ning Wang, 619–33. Springer Proceedings in Business and Economics. Springer International Publishing.

Buecher, Daniel, Yves-Simon Gloy, Bernhard Schmenk, and Thomas Gries. 2018. “Individual On-Demand Produced Clothing: Ultrafast Fashion Production System.” In Customization 4.0, edited by Stephan Hankammer, Kjeld Nielsen, Frank T. Piller, Günther Schuh, and Ning Wang, 635–44. Springer Proceedings in Business and Economics. Springer International Publishing.

EMS-CHEMIE Holding AG. 2021. “EMS-GRILTECH - Grilon.” 2021. https://www.emsgriltech.com/en/products-applications/products/grilon/.

Eschen, Kevin, Julianna Abel, Rachael Granberry, and Brad Holschuh. 2018. “Active-Contracting Variable-Stiffness Fabrics for Self-Fitting Wearables.” Proceedings of the ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems. ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems 2018 (September).

Gramazio, Fabio, Matthias Kohler, and Jan Willmann. 2014. The Robotic Touch: How Robots Change Architecture. Zurich: Park Books.

Haar, Sherry J. 2011. “Studio Practices for Shaping and Heat-Setting Synthetic Fabrics.” International Journal of Fashion Design, Technology and Education 4 (1): 31–41.

Knittel, Chelsea, Diana Nicholas, Reva Street, Caroline Schauer, and Genevieve Dion. 2015. “Self-Folding Textiles through Manipulation of Knit Stitch Architecture.” Fibers 3 (4): 575–87.

Luo, Jin, Fumei Wang, Guangbiao Xu, and Hoe Hin Chuah. 2011. “Effects of Fiber Crimp Configurations on the Face Texture of Knitted Fabrics Made with PTT/PET Bicomponent Fibers.” Journal of Engineered Fibers and Fabrics 6 (1): 155892501100600.

M1PLUS (version 7.2.037). 2021. STOLL. https://www.stoll.com/en/software/m1plusr/.

Narayanan, Vidya, Lea Albaugh, Jessica Hodgins, Stelian Coros, and James McCann. 2018. “Automatic Machine Knitting of 3D Meshes.” ACM Transactions on Graphics 37 (3): 35:1-35:15.

Pavko-Čuden, Alenka, and Darja Rant. 2017. “Multifunctional Foldable Knitted Structures: Fundamentals, Advances and Applications.” Textiles for Advanced Applications, September.

Perera, Ayomi Enoka, Gamini Lanarolle, and Ravindi Jayasundara. 2019. “Effects of Panel Parameters and Heat Setting Temperature on Thermal Shrinkage of Heat Cured Polyester Plain Knitted Fabric Panels Statistical Modeling Approach.” In 2019 Moratuwa Engineering Research Conference (MERCon), 722–26.

Perera, Henadeera Arachchige Ayomi Enoka, and Wilathgamuwage Don Gamini Lanarolle. 2020. “Comparative Study on the Thermal Shrinkage Behaviour of Polyester Yarn and Its Plain Knitted Fabrics.” The Journal of The Textile Institute 111 (12): 1755–65.

Papadopoulou, Athina, Jared Laucks, and Skylar Tibbits. 2017. “Auxetic Materials in Design and Architecture.” Nature Reviews Materials 2 (12): 1–3. https://doi.org/10.1038/natrevmats.2017.78.

Prahsarn, Chureerat, Wattana Klinsukhon, Nanjaporn Roungpaisan, and Natee Srisawat. 2013. “Self-Crimped Bicomponent Fibers Containing Polypropylene/Ethylene Octene Copolymer.” Materials Letters 91 (January): 232–34.

Rutten, D. 2021. Grasshopper 3d (version 1.0.0007). Robert McNeel & Associates. https://www.rhino3d.com/.

Rwei, S., Y.T. Lin, and Yuan-Yuan Su. 2005. “Study of Self-Crimp Polyester Fibers.” Polymer Engineering & Science 45 (June): 838–45.

Scorpion (version 0.2). 2017. https://www.food4rhino.com/en/app/scorpion.

Scott, Jane. 2013. “Hierarchy in Knitted Forms: Environmentally Responsive Textiles for Architecture.” In ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-1-926724-22-5] Cambridge 24-26 October 2013), Pp. 361-366. CUMINCAD.

Spencer, David J. 2001. Knitting Technology: A Comprehensive Handbook and Practical Guide. CRC Press.

Tessmer, Lavender, Carmel Dunlap, Bjorn Sparrman, Schendy Kernizan, Jared Laucks, and Skylar Tibbits. 2019. “Active Textile Tailoring.” In ACM SIGGRAPH 2019 Emerging Technologies, 1–2. SIGGRAPH ’19. New York, NY, USA: Association for Computing Machinery.

Wu, Kui, Hannah Swan, and Cem Yuksel. 2019. “Knittable Stitch Meshes.” ACM Transactions on Graphics 38 (1): 1–13.

IMAGE CREDITS

All drawings and images by the authors.

Lavender Tessmer is a PhD student in Design and Computation in the Department of Architecture at the Massachusetts Institute of Technology.

Skylar Tibbits is an Associate Professor of Design Research and director of the Self-Assembly Lab in the Department of Architecture at the Massachusetts Institute of Technology.