WraPr: Spool-Based Fabrication for Object Creation and Modification

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ABSTRACT

We propose a novel fabrication method for 3D objects based on the principle of spooling. By wrapping off-the-shelf materials such as thread, ribbon, tape or wire onto a core structure, new objects can be created and existing objects can be augmented with desired aesthetic and functional qualities. Our system, *WraPr*, enables gesture-based modelling and controlled thread deposition. We outline and explore the design space for this approach. Various examples are fabricated to demonstrate the possibility to attain a range of physical and functional properties. The simplicity of the proposed method opens the grounds for a light-weight fabrication approach for the generation of new structures and the customization of existing objects using soft materials.

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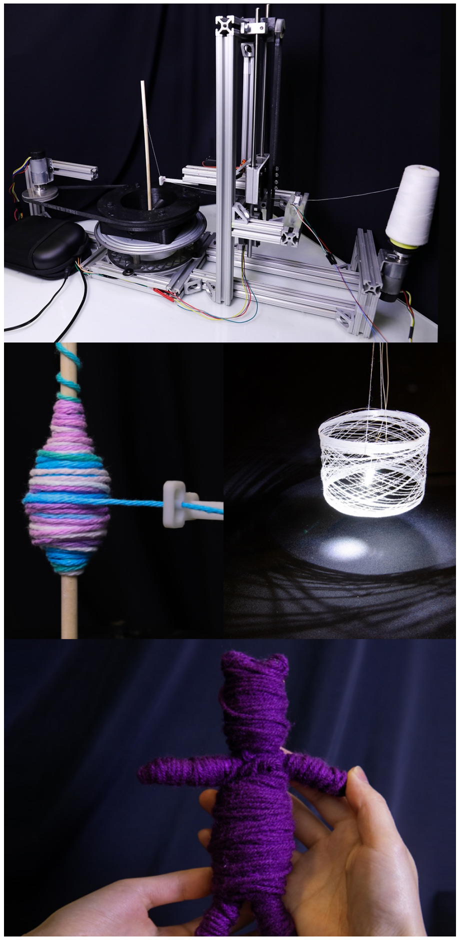

Figure 1: WraPr is a spool-based fabrication system that can be used for object creation and modification.

CCS CONCEPTS

• **Human-centered computing** → **Interactive systems and tools**; Gestural input.

KEYWORDS

Fabrication, Soft Materials, Rapid Prototyping, Textiles

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INTRODUCTION

Personal Fabrication is a trending topic in HCI [6]. Technologies such as 3D Printing, Laser-cutting, and CNC milling, enable users to manufacture a large variety of objects using digital tools. More recently, textile fabrication technologies like knitting [5, 17] or felting [12] have come into focus as well. Many additive manufacturing technologies use a base material that comes delivered in coils – filament for 3D printers, as well as yarn and thread for textile manufacturing. These coils are created by industrial machines at a breathtaking speed and high accuracy. Could this process be used to create objects, similar to how other industrial techniques have been adapted for personal fabrication?

This work investigates spooling as means to produce different structures by controlling where thread, and other soft filament-like materials are deposited from a source-spool to a target spindle. We explore the design space and show how different aspects of the process can be controlled to change the look, shape, tactility, or even add new functionality to existing objects and how spooling can be used to fabricate standalone objects without a lasting base. To illustrate these ideas we introduce *WraPr*, a system for modelling and controlled thread deposition, which we use to produce various samples that showcase the different design opportunities. The main contributions of this paper are:

- A *novel personal fabrication method* involving the deposition of off-the-shelf thread-based materials,
- an outline of the *design space* for this spooling-based method,
- the *design and implementation* of a machine (+software) for the controlled deposition of thread,
- a variety of *interaction modes and methods* to craft desired shapes for spooled-objects, and
- a range of *examples* made with this fabrication method.

RELATED WORK

Industrial *spooling, coiling, reeling and filament winding* machines [1–4] are commonly used to store and distribute a variety of materials including thread and fibers, wires, cords and cables, or to make

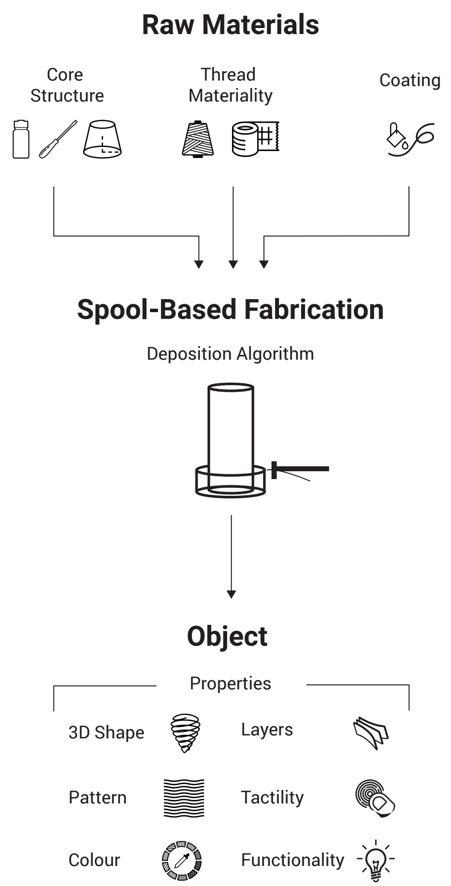

Figure 2: Design Space: three kinds of raw material can be combined and deposited in a controlled fashion to produce objects with different properties.

specialized structures. In HCI, researchers explored coiling for embedding electromagnetic coils into 3D prints [19], constructing sculptures [14], or for creating flexible tube-based displays [13]. In contrast, we seek to use spooling for physical prototyping and object augmentation. Works in the domain of *soft, textile-based fabrication* explored felting extruded yarn [12], converting 3D meshes into knitted objects [17], actuating knitted structures [5], making zippable 2D patterns of fabric [24] and stacking soft materials [20]. In addition, Rivera and Hudson [23] recently explored electrospinning, an industrial fibre production method for desktop use by modifying a 3D printer. Unlike most of these works we aim to modify the properties of existing objects by direct deposition of soft thread-based materials.

The domain of *Object Editing & Customization* was explored thoroughly in the context of 3D printing [7, 22, 27], and textile-based wearables [15]. However, this work to our knowledge is the first example of a technique that enables on-the-fly, soft-material modifications to everyday objects. This requires a way of *modelling* that considers the given shape. Tangible modelling approaches enable direct interaction with existing physical objects [8, 9, 26]. Others utilize AR environments [29] or tangible tools [10, 28]. Incremental modelling intertwines modelling and fabrication [18, 21, 31], while gesture interfaces [11, 16, 30] enable users to define objects with their hands. For WraPr we took inspiration from the light-weight, gesture-based, and object-centric modelling experience of these works.

SPOOLING FABRICATION DESIGN SPACE

In essence, spooling is quite a simple procedure wherein a thread, band, yarn or wire is wrapped onto a core object, which forms a dense, typically cylindrical body. It is commonly used in industry, e.g. to store raw thread material. We envision spooling as a low-fidelity textile fabrication system to create new and augment existing objects using common off-the-shelf threads, bands, and wires as building material. Mapping the design space (see Figure 2) to understand the design opportunities shows a number of controllable parameters (i.e. the choice of raw materials and the deposition algorithm), which can be fine-tuned to determine the resulting objects' properties. This indicates that spooling can be leveraged for a wide variety of applications, driven by both aesthetic and functional needs.

Raw Materials & Fabrication

Three different material aspects can be specified for fabrication. The **Core Structure** represents the spindle on which the material is spooled. This can be an object for augmentation (e.g. tool handle, glass) or a temporary object which is removed later (e.g. plain rod, plastic cylinder) when creating a standalone object. Spooling supports a range of different **thread material** including customary threads of various thicknesses and colours, ribbons or wires. An optional **Coating** can be applied to the thread material before it is spun onto the core structure. Glue or wax coatings improve the thread's grip on the core structure, while UV curing gel enables to create ridged objects . Besides the materials the deposition algorithm has considerable influence on the final object properties.

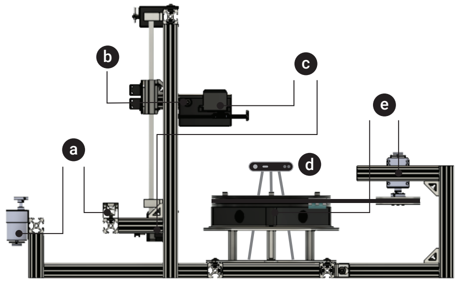

Figure 3: Schematic depiction of the WraPr hardware. a) Tensioner (DC Motor & Load Cell), b) Resin Tank, c) ThreadDeposition Head (Servo & Stepper Motor), d) Depth Sensing Camera, e) Turntable (Holder & DC Motor).

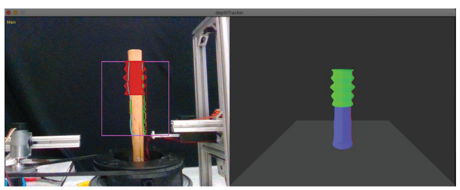

Figure 4: Screenshot of the WraPr Graphical User Interface. Left: RGB image with overlays. Right: a mesh view of the recognized core object and the designed wrap shape.

Object Properties

The characteristics of the resulting fabricated structures are shown in Figure 2. The thread placement and the number of revolutions (i.e. thread layers) at a certain level defines the **3D shape** and shapes the **pattern** on the surface level. The **colour** depends directly on the material, while the **tactility** is influenced by both thread (knitted yarn is cozy and soft, nylon cable scratchy) and coating (stiff), and the spooling sequence (even layers are smooth, crossings are bumpy). **Layers** can be used to achieve intricate texture and colour combinations, hide multiple objects within each other (similar to a *Matryoshka doll*) or combine properties. Functional thread, i.e. can be hidden underneath a decorative layer. Another option is to peel off an outer layer and exposing another one to alter properties. Finally, by using materials, such as wires, conductive yarn, or tubes, certain **functions** (e.g heating, inductive power transfer, conductive yarn for sensing) can be embedded into the the fabricated object.

SYSTEM OVERVIEW & IMPLEMENTATION

We created *WraPr*, a desktop prototyping system to explore the spooling approach (see Figure 3). The system features a turntable that holds the core object (mandrel). It is rotated by a DC motor with a rotation encoder via a friction drive belt. The height of the deposition head is controlled by a stepper motor using a timing belt, while a servomotor controls its horizontal positions to deposit the thread close to the object. To control the tension of the deposition material the source spool is mounted on a DC motor, which rotates according to the reading from a mini load cell. A optional resin tank can be used to coat the thread prior to its deposition. The components are controlled by two Arduino Unos topped with Adafruit and Rugged Circuit motor shields respectively. A depth camera (RealSense D415) that faces towards the turntable captures the core structure and enable user interaction, featuring various interaction modes. The user-interface (see Figure 4) is implemented in Processing, using OpenCV and blob detection for image processing and gesture detection.

Fabrication Pipeline

The process for creating an object involves four basic steps. (1) **Preparation** — Load and secure the core structure, the thread-based material, and fill the reservoir with a coating if desired. Thread the material through the tensioner, reservoir, and deposition head and secure it to the core structure with a simple adhesive, such as tape or glue. (2) **Core Object Identification** — The silhouette of the core object is identified using the depth camera image and blob detection. (3) **Modelling** — Design the desired model or adaptation using the modelling method of your choice (e.g. via air sketching, or grip detection). (4) **Fabrication** — The model is transferred into a sequence of machine commands which are sent to the machine for execution. (5) **Additional Layers** — To create a multi-layer object, keep the fabricated object in place and repeat the steps using it as the core for the next layer.

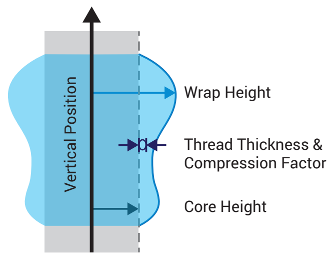

Figure 5: Essential parameters for calculating the thread deposition algorithm.

Figure 6: Two algorithms to produce cylindrical shapes. Left: (1) Side-by-Side Algorithm . Right: (2) Periodic Algorithm.

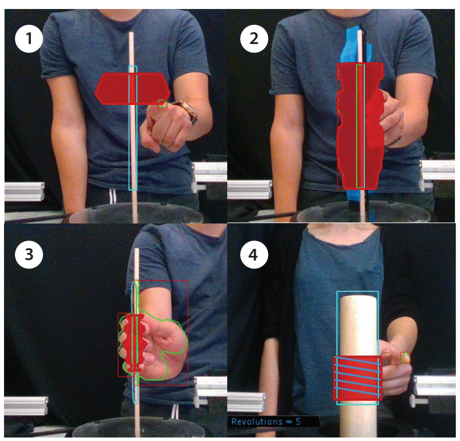

Figure 7: Interaction modes: (1) Air Sketching, (2) Object-Based Modelling, (3) Grip Detection (4) and Coil Modelling.

Instruction Generation

Once a model is created, it must be broken down into a sequence of machine instructions. Essential parameters for this calculation are shown in Figure 5. Besides the *Core Height* and *Wrap Height*, the *Thread Thickness* and *Thread Compression Factor* (Young's Modulus) are essential as they define the amount of volume the thread fills per revolution. The thinner the thread, the more revolutions are necessary to achieve volume. Aside from generating pattern instructions, we developed two general approaches for spooling volumetric shapes. (1) Winding the thread *side-by-side* sequentially results in a smooth layered structure (see Figure 6, left). However, depending on the thread, this approach can be prone to unraveling. (2) Moving the head *periodically* up and down while rotating the turntable (see Figure 6, right) leads to in more yarn crossings, which helps to pull the rims of the resulting object towards the center. This helps to mitigate layers of yarn unravelling outwards. The benefits of both strategies can be combined by using (2) to create a stable core covered by (1) for a smooth surface.

USER INTERACTION & MODELLING

With *WraPr*, we explore light-weight gestural interaction methods as a means for modelling to compliment the cylindrical nature of this method and allow for the tweaking of existing objects.

- **Air Sketching** Leveraging depth information, the fingertips of one's hand can be identified and used for gesture drawing desired additions of the base object in-place mid-air (see Figure 7.1). Silhouettes are displayed in real-time on a screen as feedback and can be reshaped by the user.
- **Object-Based Modelling** Another option for modelling is to copy the outline from an existing object by placing a physical object next to the core structure (see Figure 7.2).
- **Grip-Detection for Modelling** A related modelling strategy can be used for creating customized grips. By grasping an object in one's hand, the system determines a grip complementing the user' fingers by inverting the detected height information as shown in Figure 7.3.
- **Coil Modelling** *WraPr* can also create wire coils for electric applications. The respective interaction mode lets users define the covered area and the number of revolutions (see Figure 7.4). This allows adapting the properties of the coil depending on the desired application (e.g. heating or induction).
- **Pattern Creation** To create aesthetic patterns, one can use define the area and use predefined algorithms or directly script and test pattern ideas via a programming interface.

FABRICATION EXAMPLES

WraPr can be used to modify existing objects, as well as create a variety of new objects. **Custom grips** on existing objects can be created with little effort using the grip-detection-based modelling method. More **complex 3D shapes**, such as a teddy bear can be made by assembling a series of fabricated pieces with a flexible copper wire for a core. **Decorative items** such as candle holders

Figure 8: Different applications made with WraPr (from top to bottom): a pencil grip, a handle grip, a teddy bear, decorative candle jars, a series of lampshades with different light permeability and shadow patterns, a heating cup sleeve, and a pair of inductive bracelets that shine brighter when placed closer together.

can be made by spinning different yarn patterns. By coating thread with UV curing gel, **standalone objects** without a permanent core can be made such as lampshades. By applying multiple layers consisting of different material, one can achieve **functional layers**. For example, one can augment a drinking mug with a heated cup sleeve. Silicon self-fusing tape sandwiching a layer of nichrome 80 wire (32 gauge), topped with colorful yarn can be used to produce a pleasant aesthetic and tactile experience. *WraPr* can also be used to create simple **functional wearables**, e.g. a pair of bracelets, each containing wire coils for induction, one as a transmitter and the other as a receiver. When placed adjacent to one another, they light up. Examples for these applications are shown in Figure 8.

TECHNICAL DISCUSSION & LIMITATIONS

Using thread as a building material provides a unique set of design possibilities, challenges and constraints. Fixation is achieved by rotation around the core structure as spooling does not include thread loops or knots. While flat bands can be stacked, common untreated thread neither bonds to itself nor stacks upon itself in a stable manner and does not support overhangs. One important aspect to consider is **slip**, which makes threads shift away from their intended placement. It can be controlled by maintaining sufficient **tension** when depositing the thread but is also affected by the **type of threading material** and the *surface quality* of the core object. Unsurprisingly, threads with a slick surface (e.g. knitted yarn) are more prone to slipping than threads with a rougher surface texture (e.g. mercerized cotton embroidery thread) which maintain their position better. *Coating* can help to reduce slip. For instance, the sticky consistency of UV curing gel keeps the thread in place during fabrication and once cured, the thread is fixed. The thread's **Young's Modulus** must also be considered as it may lead to variations in the thread diameter during fabrication. Although our examples show uniform shapes, tests show that it is possible to use different sine functions to produce asymmetrical shapes due to the periodic nature of the fabrication method.

CONCLUSION AND FUTURE WORK

In this work, we explored spooling fabrication method for object creation and augmentation. While the general perception might be that this technique is quite restrictive, our exploration of the design space revealed that there is a large number of object properties that can be controlled. We implemented a prototypical thread depositing machine that was then used to create a variety of fabrication examples to highlight the versatility of the spooling approach to address aesthetic and ergonomic customization, as well as functional augmentation. The resulting objects show that the method has a lot of potential for the creation of new structures, or the customization of objects using soft materials. In the future it would be exciting to explore more *degrees of freedom* by enabling tilting the wrapped object. Other interesting possibilities involve to *undo* parts of the fabrication process or to implement a *closed-loop system* [25] wherein the shape error can be detected by the camera and used for a constant correction.

REFERENCES

[1] 2019. Filament Winding. https://www.advancedcomposites.com/composites-manufacturing/filament-winding/.

[2] 2019. Reel Power Industrial. https://www.reelpowerind.com.

[3] 2019. Spooling & Winding Machines. https://www.showmarkcorp.com.

[4] 2019. Spooling Winding Patterns. https://www.animatics.com/support?id=239#spooling-pattern.

[5] Lea Albaugh, Scott Hudson, and Lining Yao. 2019. Digital Fabrication of Soft Actuated Objects by Machine Knitting. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 184, 13 pages. https://doi.org/10.1145/3290605.3300414

[6] Patrick Baudisch and Stefanie Mueller. 2016. Personal Fabrication. *Foundations and Trends® in Human-Computer Interaction* 10, 3-4 (2016), 165–293. https://doi.org/10.1561/1100000055

[7] Xiang 'Anthony' Chen, Stelian Coros, Jennifer Mankoff, and Scott E. Hudson. 2015. Encore: 3D Printed Augmentation of Everyday Objects with Printed-Over, Affixed and Interlocked Attachments. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 73–82. https://doi.org/10.1145/2807442.2807498

[8] Sean Follmer, David Carr, Emily Lovell, and Hiroshi Ishii. 2010. CopyCAD: Remixing Physical Objects with Copy and Paste from the Real World. In *Adjunct Proceedings of the 23Nd Annual ACM Symposium on User Interface Software and Technology (UIST '10)*. ACM, New York, NY, USA, 381–382. https://doi.org/10.1145/1866218.1866230

[9] Sean Follmer and Hiroshi Ishii. 2012. KidCAD: Digitally Remixing Toys Through Tangible Tools. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12)*. ACM, New York, NY, USA, 2401–2410. https://doi.org/10.1145/2207676.2208403

[10] Tovi Grossman, Ravin Balakrishnan, and Karan Singh. 2003. An Interface for Creating and Manipulating Curves Using a High Degree-of-freedom Curve Input Device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 185–192. https://doi.org/10.1145/642611.642645

[11] Yoon Chung Han and Byeong-jun Han. 2014. Virtual Pottery: A Virtual 3D Audiovisual Interface Using Natural Hand Motions. *Multimedia Tools and Applications* 73, 2 (nov 2014), 917–933. https://doi.org/10.1007/s11042-013-1382-3

[12] Scott E. Hudson. 2014. Printing Teddy Bears: A Technique for 3D Printing of Soft Interactive Objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 459–468. https://doi.org/10.1145/2556288.2557338

[13] Yuki Inoue, Yuichi Itoh, and Takao Onoye. 2018. TuVe: A Flexible Display with a Tube. In *SIGGRAPH Asia 2018 Emerging Technologies (SA '18)*. ACM, New York, NY, USA, Article 16, 2 pages. https://doi.org/10.1145/3275476.3275487

[14] Markus Kayser, Levi Cai, Sara Falcone, Christoph Bader, Nassia Inglessis, Barrak Darweesh, and Neri Oxman. 2018. Design of a Multi-Agent, Fiber Composite Digital Fabrication System. *Science Robotics* 3, 22 (2018). https://doi.org/10.1126/scirobotics.aau5630

[15] Joanne Leong, Patrick Parzer, Florian Perteneder, Teo Babic, Christian Rendl, Anita Vogl, Hubert Egger, Alex Olwal, and Michael Haller. 2016. proCover: Sensory Augmentation of Prosthetic Limbs Using Smart Textile Covers. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 335–346. https://doi.org/10.1145/2984511.2984572

[16] Stefanie Mueller, Anna Seufert, Huaishu Peng, Robert Kovacs, Kevin Reuss, François Guimbretière, and Patrick Baudisch. 2019. FormFab: Continuous Interactive Fabrication. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '19)*. ACM, New York, NY, USA, 315–323. https://doi.org/10.1145/3294109.3295620

[17] Vidya Narayanan, Lea Albaugh, Jessica Hodgins, Stelian Coros, and James Mccann. 2018. Automatic Machine Knitting of 3D Meshes. *ACM Trans. Graph.* 37, 3, Article 35 (Aug. 2018), 15 pages. https://doi.org/10.1145/3186265

[18] Huaishu Peng, Jimmy Briggs, Cheng-Yao Wang, Kevin Guo, Joseph Kider, Stefanie Mueller, Patrick Baudisch, and François Guimbretière. 2018. RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, New York, NY, USA, Article 579, 12 pages. https://doi.org/10.1145/3173574.3174153

[19] Huaishu Peng, François Guimbretière, James McCann, and Scott Hudson. 2016. A 3D Printer for Interactive Electromagnetic Devices. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology (UIST '16)*. ACM, New York, NY, USA, 553–562. https://doi.org/10.1145/2984511.2984523

[20] Huaishu Peng, Jennifer Mankoff, Scott E. Hudson, and James McCann. 2015. A Layered Fabric 3D Printer for Soft Interactive Objects. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1789–1798. https://doi.org/10.1145/2702123.2702327

[21] Huaishu Peng, Rundong Wu, Steve Marschner, and François Guimbretière. 2016. On-The-Fly Print: Incremental Printing While Modelling. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 887–896. https://doi.org/10.1145/2858036.2858106

[22] Raf Ramakers, Fraser Anderson, Tovi Grossman, and George Fitzmaurice. 2016. RetroFab: A Design Tool for Retrofitting Physical Interfaces Using Actuators, Sensors and 3D Printing. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 409–419. https://doi.org/10.1145/2858036.2858485

[23] Michael L. Rivera and Scott E. Hudson. 2019. Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, Article 204, 12 pages. https://doi.org/10.1145/3290605.3300434

[24] Christian Schüller, Roi Poranne, and Olga Sorkine-Hornung. 2018. Shape Representation by Zippables. *ACM Trans. Graph.* 37, 4, Article 78 (July 2018), 13 pages. https://doi.org/10.1145/3197517.3201347

[25] Pitchaya Sitthi-Amorn, Javier E. Ramos, Yuwang Wangy, Joyce Kwan, Justin Lan, Wenshou Wang, and Wojciech Matusik. 2015. MultiFab: A Machine Vision Assisted Platform for Multi-material 3D Printing. *ACM Trans. Graph.* 34, 4, Article 129 (July 2015), 11 pages. https://doi.org/10.1145/2766962

[26] Hyunyoung Song, François Guimbretière, Chang Hu, and Hod Lipson. 2006. ModelCraft: Capturing Freehand Annotations and Edits on Physical 3D Models. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology (UIST '06)*. ACM, New York, NY, USA, 13–22. https://doi.org/10.1145/1166253.1166258

[27] Alexander Teibrich, Stefanie Mueller, François Guimbretière, Robert Kovacs, Stefan Neubert, and Patrick Baudisch. 2015. Patching Physical Objects. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15)*. ACM, New York, NY, USA, 83–91. https://doi.org/10.1145/2807442.2807467

[28] Christian Weichel, Jason Alexander, Abhijit Karnik, and Hans Gellersen. 2015. SPATA: Spatio-Tangible Tools for Fabrication-Aware Design. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15)*. ACM, New York, NY, USA, 189–196. https://doi.org/10.1145/2677199.2680576

[29] Christian Weichel, Manfred Lau, David Kim, Nicolas Villar, and Hans W. Gellersen. 2014. MixFab: A Mixed-reality Environment for Personal Fabrication. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems (CHI '14)*. ACM, New York, NY, USA, 3855–3864. https://doi.org/10.1145/2556288.2557090

[30] Karl D.D. Willis, Juncong Lin, Jun Mitani, and Takeo Igarashi. 2010. Spatial Sketch: Bridging Between Movement & Fabrication. In *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '10)*. ACM, New York, NY, USA, 5–12. https://doi.org/10.1145/1709886.1709890

[31] Amit Zoran and Joseph A. Paradiso. 2013. FreeD: A Freehand Digital Sculpting Tool. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 2613–2616. https://doi.org/10.1145/2470654.2481361