

Fold Printing: Using Digital Fabrication of Multi-Materials for Advanced Origami Prototyping

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Abstract



Figure 1. Advanced multi-material prototypes. Left: a set of regular corrugations (waterbomb, miura, and yoshimura). Center: Irregular yoshimura-based fashion prototype in felt, polymer and elastomer. Right: Irregular waterbomb pattern formed into a cap.

General foldability in origami is now less subjective than suggested by difficulty assignments in the origami community: beginner, intermediate, advanced and super complex. Specific cases of foldability issues have clear methods, such as flat-foldability [Kawasaki 1989; Hull 1994], rigid-foldability [Tachi 2009a; Tachi 2009b; Demaine and Demaine 2002]. Material properties of folds in paperboard vs a perfect hinge are given as measure of foldability in [Paperboard 1993:186–193], and density of folds is factored in pattern optimisation by [Dudte et al. 2016]. We contend that regularity of a crease pattern is an additional factor in evaluating a measure of *complex-foldability*. A regular pattern has folds located on landmarks, such as parallel, perpendicular, or fold-based divisions such as $45/22.5^\circ$, or $15/30/60^\circ$, and on equally spaced grid: adjacent folds have utility in forming the next fold. An irregular pattern has no landmarks it is totally irregular, as adjacent folds have no utility in forming the next fold it therefore has low-foldability. Our work is of general benefit for common folding applications, but particularly benefits folding of irregular, non-flat-foldable, non-rigid, and low-degree-of-foldability origami by addressing properties of the material. Physical prototyping can validate a given folding design, and the first choice of material is paper. It is strong, thin, retains elastic memory of folds, and can be pre-scored by machine to increase foldability of complex patterns. However properties that make paper readily accept

creases, also make it vulnerable to corruption. Unwanted creases impact the aesthetic of a design, functionally they impact the accuracy of subsequent folds, and can introduce buckling that corrupts a collapsing pattern. Paper prototypes are delicate, and even more so for low-degree-of-foldability origami.

We present a method to increase foldability of complex folding patterns by digital fabrication of multi-material composites with rigid plates separated by perfect hinges. Our work extends existing methods in the field of fabrication of folded geometries, especially computationally generated folding patterns such as those produced by Resch, Lang, Tachi, and Mitani [Resch and Christiansen 1970; Lang 1998; Tachi 2010; Tachi 2009a; Mitani 2009]. Recently, digital fabrication techniques have extended the origami toolkit. Plotting, laser scoring, perforation of paper, polymers, and textiles [Gardiner 2013:21; Resch 1992], etching of metals [Kuribayashi et al. 2006], electroplating [De-Ruysser 2009], as well as pleating by pressure and heat [Gardiner 2015; Sallas and Zscheckel 2010:20] are commonly known methods in industry and practices of origami artists.

We add to these our method for prototyping origami patterns in durable, low-cost, easily acquired materials, by using an off-the shelf FDM (Fuse Deposit Modelling) 3D Printer to increase foldability of regular and irregular designs. The key features of our method is to 3D print rigid polymer plates onto textile surfaces, and to treat with heat pressing, followed by optional application of elastomers to introduce elastic memory and allow per-instance setting the folded-shape memory of the finished Folded-Textile-Polymer-Elastomer composite (FTPE). Similar in function to textile electroplating technique [De-Ruysser 2009], and a cement textile process [van der Woerd et al. 2015] with the advantages that no pre-tooling or chemistry beyond polymer filaments are required, and due to the digital fabrication workflow, designs can be altered with each iteration. We detail geometric properties such as fold width, print settings, machine calibration, and filament and textile selection, and conclude with application prototypes, including soft robotics actuators.

We also present a custom built Cartesian robot, designed for prototyping sheets up to 105x105cm to accommodate an increased complexity in number of folds per model, and increased utility by producing prototypes at scale. We evaluate our methods by proof-of-concept in a variety of design targets, featuring regular and irregular software generated folding patterns. We compare foldability in terms of time-to-fold laser-scored paper with FTPEs, compare processing techniques, and critically evaluate physical and aesthetic properties of the completed prototypes.

Our results show our method improves foldability of complex geometries, eliminating the correlative problems of paper, having a marked increase of foldability for low-degree-of-foldability irregular patterns. Affording potential for researchers to investigate material function—such as low-cost prototyping of origami based-soft-robotic actuators—and aesthetics due to freedom of geometry. Further work suggests an increased application domain for origami prototypes through experimental multi-material combinations, including variant 3D printing filaments such as conductive carbon, flexible nylons, with an assortment of textiles and other sheet materials.

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