Title:
Shape-Shifting Solutions: An Origami-Inspired Reconfigurable Gripper for Limp Textile Automation

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Introduction:

Polymer composites are lightweight materials that offer superior stiffness and strength. However, currently there are no comprehensive, efficient, rapid, semi-automatic, or automatic solutions for handling limp composite textiles (or other similar materials). Manual operations (layups) are required for the material handling of flexible components such as fabrics and woven textiles. This manufacturing strategy is labor-intensive, presents safety issues, and creates process bottlenecks [7, 13]. Draping, a manual technique for positioning textile patterns onto a mold for composite manufacturing, depends on fabric properties like in-plane shear, bending stiffness, and structural stability, as well as the mold's geometric features [2, 4]. Fabrics made from heavy, coarse yarns with dense construction drape poorly, while those with long floats and filament yarns with little twist drape much better. The flexible nature of these textiles allows them to bend and conform to varying curvatures (i.e., mold surfaces). This compliance coupled with a fabric's surface texture, construction, and variability in geometry (i.e., shape, size, presence of cut-outs and slits), creates automation challenges related to reliable handling without inherent damage to the material. Unfortunately, the significant mass reduction potential associated with polymer composite fiber-based components is offset by high labor intensity and the associated long 'pick and place (draping)' cycle times. These repetitive handling tasks often involve awkward postures, leading to work-related musculoskeletal disorders, resulting in increased absences, productivity loss, and higher healthcare expenses [13].

Automation should be employed when the tasks are repetitive, risky, and remote. Production cycle times in automotive production facilities are approximately 65 jobs/hr, and many assembly components could be required per vehicle, scaling the production quantities. Consequently, we need an automation solution, but automation is typically introduced for rigid components. Therefore, it is required to transform the flexible materials into a rigid structure without introducing damage (i.e., using a 'needle' gripper to pick up the material). The pick and place activity can be divided into three stages: pick→transfer→place. A solution needs to be developed that 'grips' the fabric for the picking element, is rigid during the transfer, and provides compliance to adapt to a mold's surface for the placing element. The goal of this research is to develop a reconfigurable, self-collapsing origami gripper for textile pick and place onto non-planar mould surfaces, thereby addressing the need for a low-complexity automation solution that is easily adaptable to various fabrics, simple to install, and minimizes material damage or residue. For the proof of concept, material extrusion based additive manufacturing (AM) strategies are leveraged to build and test gripper iterations.

To handle non-rigid parts, techniques include mechanical grasping, ingressive grasping (such as needle grippers and Velcro systems), and adhesion grasping (using vacuum/suction cups, electromagnetic or electrostatic forces, air jets, or cryogenic principles). Each technique has specific advantages and limitations depending on the material and shape of the object [5]. These handling methods encounter diverse challenges, ranging from fabric damage, high costs, and excessive energy consumption to inflexibility and complexity. Soft robots, with pliable bodies that mimic biological systems, provide deformable structures and muscle-like actuation for enhanced flexibility. These grippers are particularly effective in handling fragile or deformable objects by conforming to object contours, securely holding complex geometries with uneven surfaces and varying sizes and ensuring safe and efficient handling while minimizing the risk of damage [11, 14, 8, 9]. However, soft robotics solutions documented in the literature primarily rely on either tendon-driven or pneumatic mechanisms, showcasing limitations in adaptability and controllability during operation. Therefore, another approach is required.

Main Idea:

The Miura-Ori, also known as the Miura map-fold, is a traditional origami fold based on a tessellation of slanted parallelograms (Fig. 1). It is used to fold large flat geometries into smaller surface areas and can be refolded and returned to its collapsed shape – thus described as “shape-memory” origami [10].

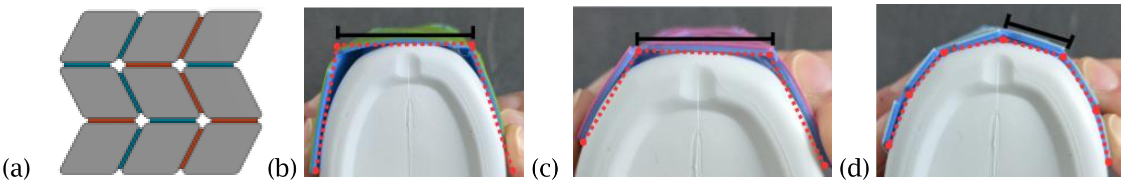

Fig. 1: (a) Miura-Ori CAD illustrating the peak (red) and valley (blue) folds, (b) example of Miura-Ori's shape adaptivity along curved surface (bending) with 35mm (c) 25 mm and (d) 12.5 mm panel sizes.

The kinematics are characterized as “in-plane” and “out-of-plane", where the geometry has motion following the folds of the origami, and motion via twisting and bending, respectively [12]. Miura-Ori can create a structure that can collapse and conform to different curvatures [3]. As observed in previous work, larger parallelogram panels are better for adapting to gradual “S” shape curvature, and smaller panels follow tighter curvature with less surface discontinuity (Fig. 1) [13]. The folding nature of the Miura-Ori is influenced by its geometry, meaning the number of parallelograms, the distance between each of them, and the thickness of the fold. Preliminary research has been performed that illustrated the potential of this solution [13]; however, this research focused on developing small compliant grippers. The concepts must be scaled up to determine the feasibility for larger and more complex fabric shapes.

A four-part experimental methodology was taken for this research: (i) a complex 'W' shape fabric sample with an internal slit was chosen to represent the intricacies of textiles handled in industry (Fig. 2 (b)). (ii) A non-flat mold surface with a slight curvature was designed to simplify the tessellation complexity of the gripper and assess its ability to conform to non-planar geometries (Fig. 2 (a)). (iii) Based on existing literature [3, 13], a tessellation pattern for the Miura-Ori fold was determined to create a structure capable of collapsing and conforming. (iv) The compliant gripper was then fabricated using material extrusion-based additive manufacturing (AM) with PLA for rigid panels and X-920 Flex for living hinges. Due to 3D printer constraints, the gripper was assembled from sub-modules. Manual pick and place tests were conducted (Fig. 3) to validate the gripper's ability to pick the 'W' shaped fabric. Compression data, including open and closed diagonal distances, was collected to quantify the gripper's characteristics and support the design of a collapsing frame for future automated use (Fig. 2 (c) and (d) and Fig. 5).

The Miura-Ori fold successfully picks the silk-like sample. This was determined a successful test by the gripper's ability to lift the fabric with minimal surface pressure, fully accommodate the 'W' (irregular geometry and internal slit), and securely retain the fabric within its folds once collapsed. The unique advantage of this Miura-Ori solution is its ability to transform the flexible and limp fabric into a rigid body as it collapses.

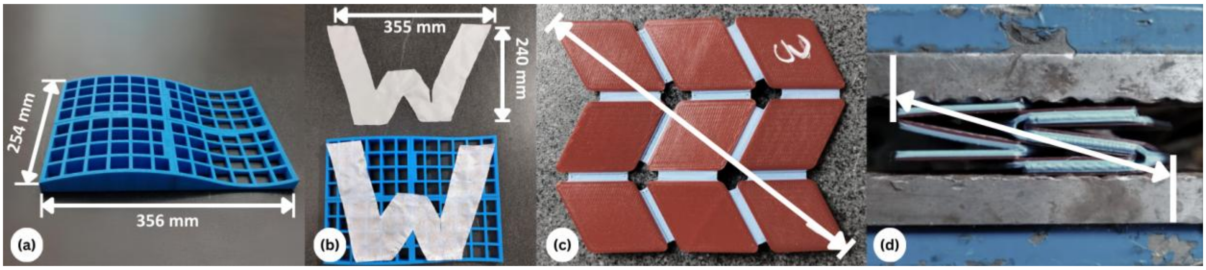

Fig. 2: (a) the mold, (b) the W shape, (c) open gripper distance, and (d) compressed/closed gripper distance.

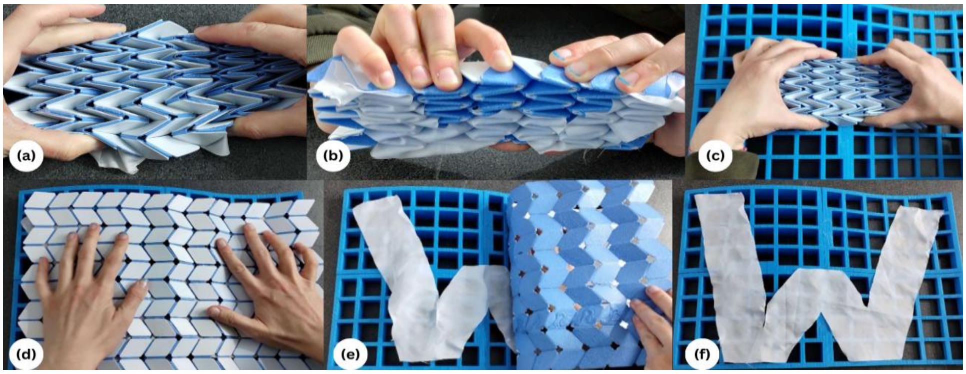

Fig. 3: Manual pick and place testing including (a) pick, (b)(c) transfer, and (d)(e)(f) place.

Thus, enabling the rapid and slip-free manual transfer of the sample, which subsequently flattens onto the mold surface. No damage to the fabric was observed, with no pulled threads or broken fibers evident. Wrinkles occurred, but a pneumatic bladder can be employed to press the gripper onto the surface, minimizing the wrinkles. This solution has been successfully applied to composite carbon fiber [1]. This proof of concept can be readily automated and is scalable (Fig. 4).

Fig. 4: Summary of explored and to be explored fabrics for pick and place via the Miura-Ori solution.

With the appropriate frame, this solution can be automated. A mounting frame was initially built with 3D printing, including moving hinges and a sliding mechanism. However, the PLA-to-PLA friction coefficient was too high for the moving parts. This design will be modified such that those contacts are replaced with circular linear bearings and a stainless-steel rod (Fig. 5).

Conclusions:

Innovative composite materials are being developed in tandem with new product ideas. However, introducing high volume production solutions for effective material handling is a roadblock.

Automation solutions need to be established to produce large quantities of components efficiently and consistently to reduce per unit costs. Employing needle grippers will damage the fibers, and vacuum related systems are not energy efficient. Other approaches, such as using soft robotic grippers with multiple robotic arms, will allow for pick-and-place actions but require more capital investment and controls to synchronize the motions, with the potential for significant wrinkling [4]. Another approach is needed.

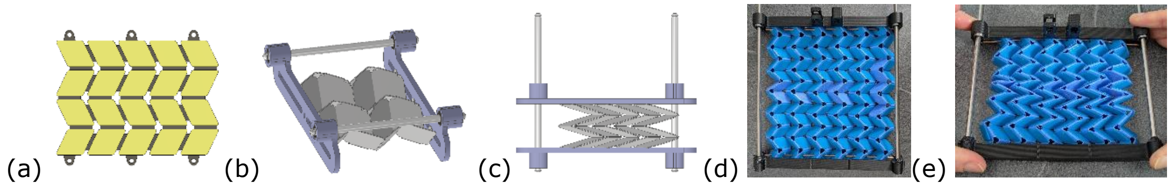

Fig. 5: (a) CAD of sample gripper with frame connections (loops) (b) partially and (c) fully compressed frame and gripper (with the linear rod and bearing) (d) fabricated prototype uncompressed and (e) partially compressed.

Contacting multiple surfaces with a controlled Miura-Ori inspired fold enables fabrics to be picked up, collapsed into a 'rigid' structure, transported, then unfolded and placed onto a curved surface, regardless of the fabric shape. This is a low-cost mechanical solution. The specialty grippers presented in this work are designed as curve-compliant, self-collapsing end-effectors, making them particularly adept at handling such limp textile materials. This is an ongoing research project – shown in Fig. 6 is a smaller-scale gripper picking and placing multiple materials.

Microfiber fabric	Cotton Fabric	Polyester Fabric	Carbon Fiber Fabric	Carbon Fiber Fabric Mold Placement Test

Fig. 6: Fabrics being picked and placed into a concave mold using a collaborative robot and a small gripper, adapted from [1].

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