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A Component-Based Approach to Automated Flexible Material Handling: Interactive Compliant Gripper Design Relative to Mold Surfaces

Morteza Alebooyeh[1], Jill Urbanic[2], Dora Strelkova[3] and Gowrav Krishna Boyapati[4]

[1]University of Windsor, alebooy@uwindsor.ca
[2]University of Windsor, jurbanic@uwindsor.ca
[3]University of Windsor, strelko@uwindsor.ca
[4]University of Windsor, boyapat@uwindsor.ca

Corresponding author: R. Jill Urbanic, jurbanic@uwindsor.ca

Abstract. The challenges posed by flexible limp fabric material handling within automated manufacturing processes are addressed in this paper. With lightweight materials, particularly fiber composites, gaining prominence across industries, the need for effective and precise fabric placements is deemed crucial. Traditional gripping methods are often found to be lacking in addressing the complexities of fabric draping, necessitating innovative solutions. The deformable, delicate, and complex nature of fabric materials, combined with intricate mold surface geometries, presents significant hurdles for achieving wrinkle-free, accurate placements. To overcome these challenges, a compliant gripper approach is proposed. Associating surface geometry analysis with gripper design, the study aims to enhance the efficiency, precision, and adaptability of fabric placement in automated manufacturing settings. The study exploits the deformable robotic gripper concepts. Compliant mechanisms include variants inspired by the Miura-fold origami approach. The facet-based representation and data processing technique used for a mold's surface allows for associations between the design parameters of the compliant grippers and the mold surface geometry. Design guidelines encompass considerations related to geometry, structural integration, surface friction enhancement, and material selection to provide a baseline framework for the interactive design of compliant grippers. Case studies highlight the merits of the approach for different surface geometries and show the potential for compliant mechanisms being employed in flexible component automation.

Keywords: Mold, Surface, Geometry Analysis, STL, Compliant Gripper, Fabric, Design Guideline.
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1 INTRODUCTION

Composite materials drive innovative research in several industries, including automotive, due to their high specific stiffness and strength in comparison to traditional engineering materials (i.e., metals and plastics) [22]. For example, in vehicle mass reduction, composites materials are used to yield strong yet light-weight parts [22]. Although known for their high specific stiffness – composite materials can exhibit degrees of flexibility and limpness. Their deformable nature creates significant automation challenges as picking motions must be done without damaging the material, and placing motions must achieve wrinkle-free and accurate placement. This research thus classifies composite materials as flexible fabrics and explores their automated handling via the design of a compliant mechanism gripper based on varying mold surface curvatures. The complexities associated with automated fabric handling are outlined by examining the limitations of current handling solutions (Table 1). Flexible fabrics are further defined, along with the deformability of composite materials, via an overview of Peirce's cantilever method for flexural rigidity.

1.1 Fabric Pick and Place

Flexible fabrics can be further defined as a 2D shape cut from an interlocking network of raw fiber materials. However, flexible fabrics are not limited to textiles, as thin plastic sheets can exhibit similar draping, bending, and wrinkling characteristics. The structure of a material may greatly affect its flexibility; thus, it is important to note the 2D and 3D weave styles of both natural and man-made materials (Figure 1).

The process flow for composite fiber components is shown in Figure 2. The fibers cannot be damaged during handling. There are many handling solutions that have been explored for the pick and place, including needle-based solutions that pierce the material and strip it from the gripper, clamping, where grippers strategically pinch the material at select points, vacuum, and adhesives. The vacuum system is expensive as it uses compressed air and limits the material transfer times for robotic systems. Adhesive-based gripper solutions can transfer or leave debris. Consequently, this is a significant automation challenge as there are many issues related to automation strategies and handling methods for high production volumes [13-14]. There is no semi-automatic or automatic solution for rapid, efficient, and reconfigurable pick and place operations of fabric materials. Thus, material handling of flexible textile/fiber components is a process bottleneck as manual operations are typically employed [10].

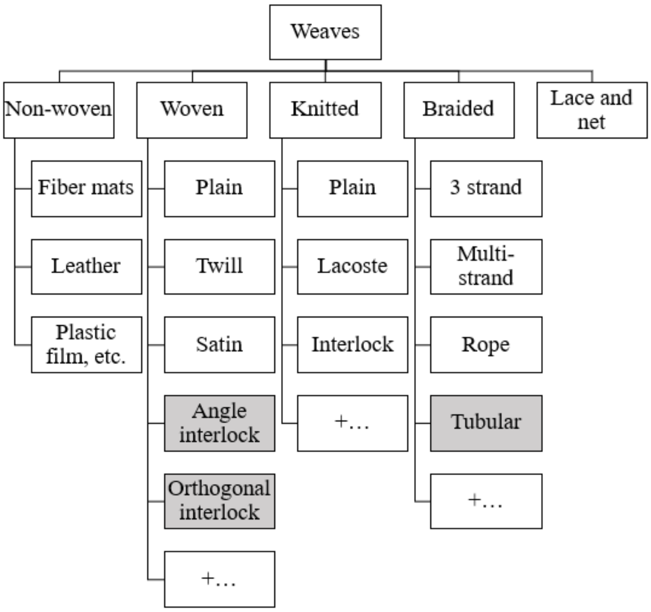


Figure 1: Fabric weave styles, where 3D weave styles are shaded.

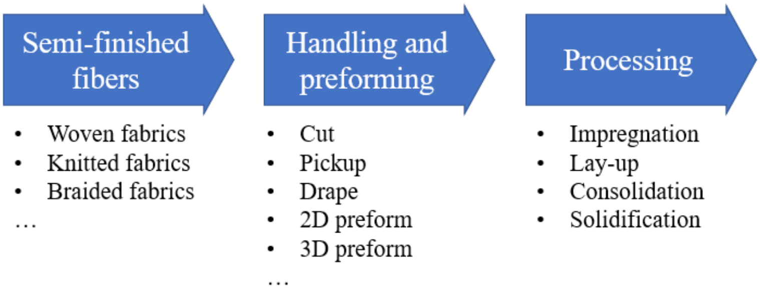


Figure 2: Process flow for molded components that incorporate composite material(s).

Several gripping solutions exist that handle the pick and place of a single sheet from a pile of textile materials. Table 1 summarizes different fabric material handling methods with their characteristics and graphic ratings of their performances. Each method enjoys some advantages but has its own drawbacks. For many applications, the fabric should not be damaged when picked, which can occur when using a needle-based or rigid clamping method. Additionally, draping within a mold needs to be fold/wrinkle-free, which is unavoidable in clamping or air flow-based methods like vacuuming [2,8].

Hence, there exists a requirement for a handling method that ensures the preservation of the fabric's integrity during the handling process. This method should additionally exhibit consistent fabric material transfers, minimizing any potential slippage. Furthermore, it should be characterized as a 'rapid' operation, aligning with the definition of rapid performance within a specific application context. The solution approach should be extensible allowing for reconfigurations to be introduced for different fabrics, mold surface sizes and variations. It should be accurate for the pick-and-place activities while offering adaptability and compliance to accommodate diverse mold surface geometries.

While there is no method that simultaneously meets all these requirements, there are avenues for enhancing the efficiency of fabric handling operations by developing novel methods. Soft and compliant grippers manufactured using inherently soft and extensible materials with deformable structures possess the intrinsic capability to fulfill the desired requirements and functions. They offer a relatively substantial number of degrees of freedom, enabling them to execute more intricate handling tasks that demand flexibility and conformity, either concerning the material or the mold surface. Consequently, the performance of fabric handling processes, encompassing picking, transferring, and placing, can all be significantly improved through the utilization of soft and compliant robotic grippers [2].

Method\Performance		Grip Force	Slippage-free	Damage-free	Placement ease on Curves/Discontin. - 2D	Placement ease on curves/Discontin. - 3D	Stretch control	Wrinkle control
Needle [2,8]		●	●	◆	◆	◆	◆	◆
Clamping	Traditional Clamps [8,25]	●	△	△	△	△	◆	◆
	Soft grippers [2,3,24]	●	●	△	△	△	△	◆
	Compliant grippers [28,29]	●	●	●	●	△	●	△
Vacuum [3,8,24]		◆	△	●	△	◆	◆	◆
Adhesion [2,3,8]		△	●	△	◆	◆	◆	◆
Air-flow [8,24]		◆	△	●	◆	◆	◆	◆
Electrostatic [3,8]		◆	△	●	◆	◆	◆	◆

Table 1: Different fabric material handling methods [2-3],[8],[24-25],[28-29].

Draping is a manual method that is used to position and conform one or more textile patterns onto a mold to manufacture composite components. The fabric properties that determine its propensity to drape (including the in-plane shear and bending stiffness, structural stability etc.) influence the placement results, which also depend on the geometric features of the mold [1-2]. A typical parameter is the bending length, which can be calculated using Peirce's cantilever method [9]. As shown in Figure 3, a specific size strip of fabric is placed on a platform and moved forward until the centerline from the edge of the platform to the leading edge of fabric makes an angle θ to the horizontal plane by self-gravity. Therefore, from Equation (1.1), the bending length c can be calculated by the cantilever length L and the angle θ:

$$c = l\left(\frac{cos(\theta/2)}{8\,tan\,\theta}\right)^{1/3} \tag{1.1}$$

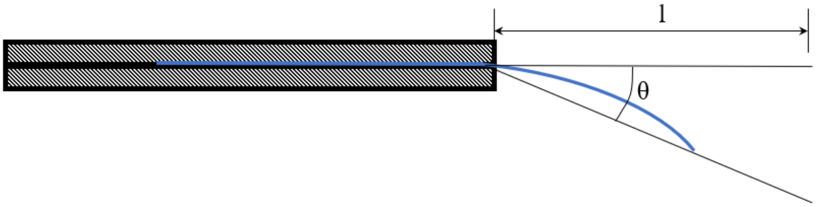


Figure 3: Peirce's cantilever method for calculation of fabric bending length (flexural rigidity).

Figure 4 shows a wrinkled fabric after a pick, move, and place operation with a dual-arm collaborative robot (cobot). A plain-woven carbon fabric was used for this operation. As aforementioned, the drapability of a fabric is the combined effect of several factors, such as the bending stiffness (flexural rigidity), e.g., limp fabric drapes closer to the mold surface and tends to conform its shape, whereas stiff fabric drapes away from the surface. The bending stiffness of the fabric itself depends upon the geometrical parameters of the fabric [25]. It is also affected by the stiffness of the fiber and the yarn, the size of the yarn, thread count, and the method of construction [6,19].

Fabrics made from heavy, coarse yarn and in dense construction do not drape well. Fabrics that have long floats in weave can be more flexible, bending more easily and improving the draping quality. If at the same time, fabrics are made from filament yarns with little twist, the draping quality is enhanced more [23].

Figure 4: An example of wrinkling after fabric placement; adapted from [2].

Figure 5 illustrates the geometric complexity of a composite mold used for the carbon fiber composite layup process. As a part of this study, mold surface geometric analysis is discussed to highlight potential regions of concern via assessing surface normal vector variations and rates of change. This will provide insight into pick and place strategies, performing [13], fabric segmentation (for similar or dissimilar materials), and placement activities. An example of segmentation is shown in Figure 6 where continuous and discontinuous fiber mats are utilized to optimize the product performance. It is shown that there are multiple material layups, and it is determined that common gripping solutions are not effective in many situations. Rapid picking of only one fabric segment from the top of the stack while introducing no damage could be an issue for these standard methods. It is proposed to employ compliant mechanisms to address the pick-and-place challenges.

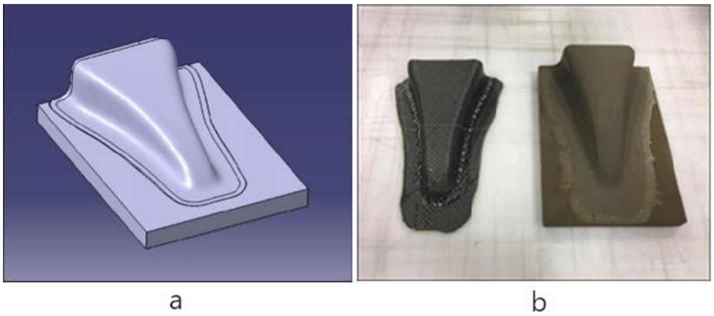


Figure 5: A composite mold used for the carbon fiber composite layup process. (a) CAD model, (b) Physical model [11].

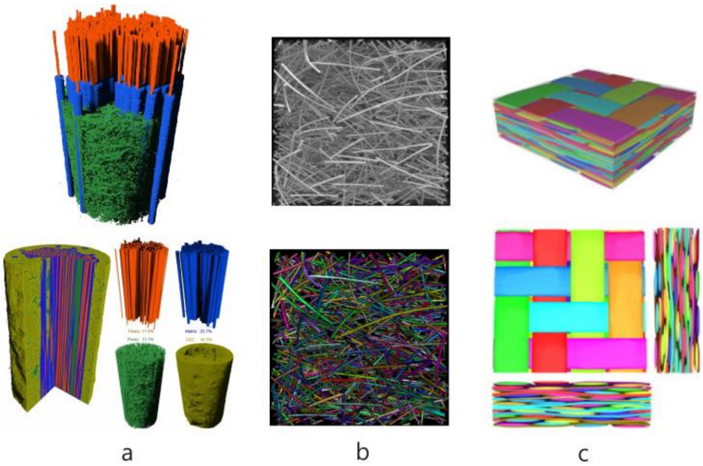


Figure 6: (a) Automatic segmentation of 3D tomography images from fiber-reinforced ceramic composites consisting of SiC-SiC matrix-fiber composite; [4], (b) Instance segmentation of fibers from CT scan [12], (c) Unit cell model of a stack of 9 layers of a twill weave fabric [32].

1.2 Compliant Mechanisms

A compliant mechanism refers to a design that incorporates flexible and deformable elements to achieve desired functionalities. Unlike traditional rigid mechanisms, compliant mechanisms use the inherent flexibility of materials to enable movement, gripping, or force application. Compliant grippers can adapt to the shape of the object being handled. These flexible elements allow the gripper to conform to irregular shapes, providing a more versatile and adaptable solution. Compliance in these mechanisms allows for better handling of objects with varying sizes, shapes, and surface irregularities. Compliant grippers are particularly useful in applications where delicate or fragile objects need to be handled without causing damage. They also find applications in scenarios where objects have complex geometry, and traditional rigid grippers may struggle to achieve a secure grip.

Compliant mechanisms are designed to adapt in a controlled manner when a load is applied. As a part of this study the potential of compliant gripper systems was studied with a focus on utilizing designs inspired by the Miura-fold and origami principles, which incorporate living hinges. The designs of these grippers are tailored according to the mold surface geometry for effective placement strategies since the compliance allows for shape conformity of a gripper-fabric set over mold surfaces during the placement stage [28]. While the integration of origami-inspired structures in robotics is not a novel concept, the study seeks to advance the field in automation of flexible materials handling by introducing a novel approach that combines the Miura-fold, a parallelogram tessellation, with living hinges. Figure 7 shows examples of grippers utilizing compliant mechanisms, including a Miura fold, living hinges, and a combination of Miura living hinges.

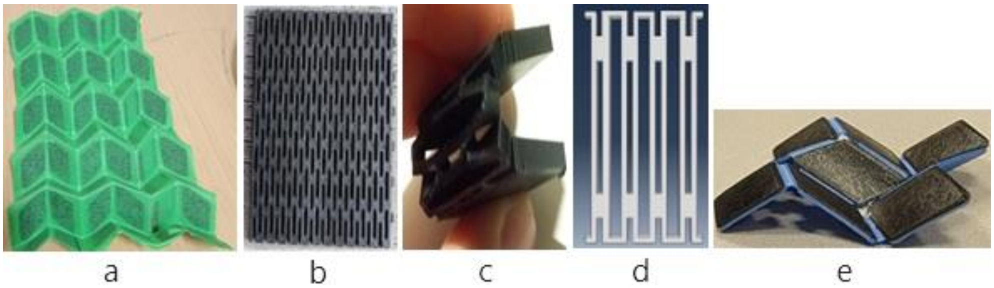


Figure 7: Compliant grippers: (a) A Miura-fold gripper, (b) An Ori-living hinge prototype [28], (c) A bent Ori-living hinge part [28], (d) CAD sketch of an Ori-living hinge design, (e) A Miura-living hinges gripper.

Traditionally, tessellation-based folds like the Miura-Ori fold have been commonly employed in the development of pincer-style gripper variants [5,24,31]. While these pincer-style end-effectors excel in reliably gripping and stabilizing volumetric objects, they may not be ideal for manipulating irregular, flexible 2D materials such as fabric layers. Pincer-style grippers may apply excessive force or cause undesirable deformation when handling fabrics, potentially leading to damage. Achieving a secure and reliable grip on fabrics that have slits or cut-outs, or other irregular geometry, may be difficult due to variability. The rigid nature of a pincer style also may impede the gripper from closely conforming to the curvature of the mold when placing a sheet of fabric onto a non-flat surface. Overall, this is undesired.

In contrast, the compliant grippers presented in this work stand out as a curve-compliant, self-collapsing end-effector. It can be designed to securely grasp and position fabric pieces on non-planar surfaces by conforming to various surface geometry contours as desired to streamline the fabric material handling operation. With this design, textiles can be gripped using an appropriate force, and geometric intricates such as slits and cut-outs can still be handled with ease. This innovation holds significant promise for automation applications involving molds with complex geometric features, intricate curvatures, and sharp corners.

Prototypes of these compliant grippers are realized using multi-material additive manufacturing (AM) methods, specifically employing Fused Filament Fabrication (FFF). However, it is important to note that when fabricating components with living hinges through FFF, certain limitations arise. These include restrictions on the gripper's loading cycles and motion capabilities. Living hinges, unlike traditional pin joints, do not offer full rotational freedom and are instead constrained by the strength of the deflecting component [27-28],[32]. To overcome those limitations in this study, AM materials with favorable flex characteristics were selected and functionally optimized gripper's geometries were utilized.

The short-term goal of this research is to identify, evaluate, predict, and pronounce potential wrinkle-generative areas or draping regions of concern of the mold surface. The long-term goal is to figure out a quantitative relationship between mold surface geometries and compliant gripper design for an effective fabric material handling operation.

To accomplish our short-term objective, evaluation and analysis tools are applied on a selection of typical mold surfaces for illustration purposes, aiming to simplify problem comprehension. These versatile and compliant tools are to be readily implemented in any advanced fiber composite industrial molding setting.

With respect to the overarching goal of this research, normal vector variations are used as a computational measure of analysis for the mold surface geometry and its impact on the compliant gripper design and, hence, on the performance of automated flexible material handling applications.

The results of this study would lead to reduced out-of-mold deformation for automatic or semi-automatic fabric draping. The holistic approach considering the interactive relationship between compliant gripper, mold, and fabric material, which embraces the effect of fabric properties on handling operation performance, will be considered in future studies [17,20]. Figure 8 provides a comprehensive visual representation of the research process concerning the automation of fabric material handling systems through the utilization of soft and compliant grippers. It encompasses prior research endeavors, underscores the current study (highlighted in green), and outlines the anticipated future outcomes.

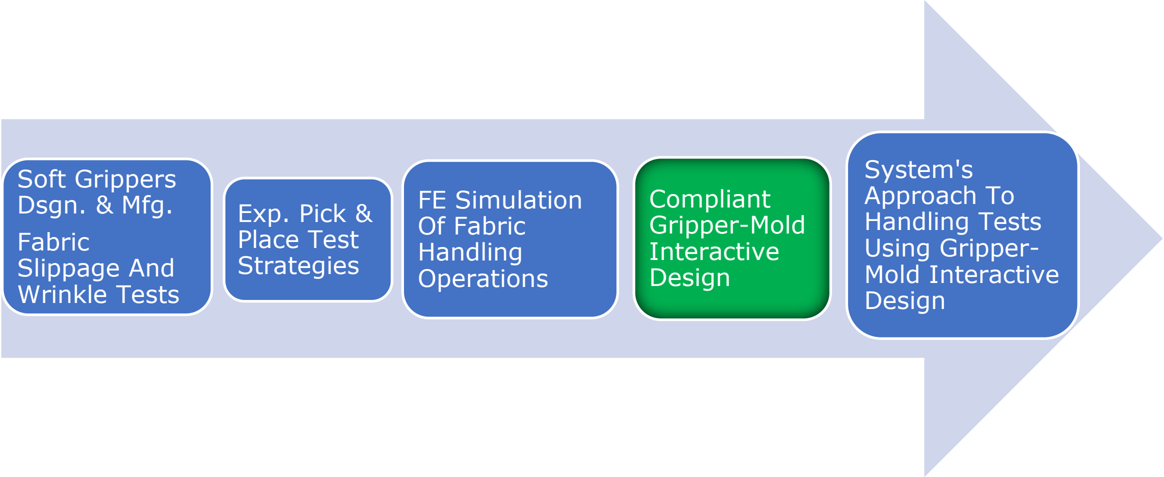


Figure 8: Holistic visual representation of the entire research process highlighting the current study.

2 BACKGROUND

Evaluating mold geometric features for mold surface redesigns, fabric panel designs (slits, holes, multiple fabric panels), and handling optimization is a necessary piece for understanding fabric-mold interactions for effective automated pick and place operations as well as the final product characteristics. Rapid, proper fabric placements without wrinkling and fitting the mold surface is the overarching goal. Complex mold surfaces can be split into individual geometric features (base surfaces). These base surfaces can be identified in the CAD models by lines and edges, drawing distinct differences between features [25]. Edges common to adjacent surfaces are used as direct links between the base surfaces. Each base surface is also identified through vertices, lengths, and radii, which can be characterized by a set number of geometric parameters. Base surfaces in industrial molds are made of several geometric features quantified through various geometric parameters that have design-specific values. Lengths and radii define either tight corners, flat segments, or long, smooth arcs that make up the complex geometry of molds and final components. Individual geometric features include flat, single curvature, or double curvature [3,17,18].

2.1 Angle Between Surfaces

Sharp edges and corners should be avoided in mold design as they can become problematic during draping in terms of conforming the fabric to the mold surface feature. These features often force the use of darting, allowing the surface to be covered without wrinkling but increasing production time since cuts must be made through the patterns [1,16]. Preliminary shear is a proposed solution for mitigating wrinkling and eliminating the need for darting.

2.2 Corners and Edges

Corners and edges that appear to have no fillets exhibit shearing characteristics that become problematic during draping. The angles between the surfaces contribute to the fabric's ability to drape over surfaces and determine how easy or difficult it is. When a fabric is placed on a mold's sharp edge and draped over the edges to cover all three surfaces, the warp and weft yarn orientations present conflicts with the alignment. Warp and weft yarns along an orthogonal crossed-edge attempt to become parallel to one another. Wrinkling is often a result of the angle between the warp and weft either becoming too large or too small due to in-plane shear [1].

3 METHODOLOGY

Two strategies are used in this research to analyze mold surfaces: a combined qualitative and semi-quantitative approach and a fully quantitative approach. The former evaluates surface and solid quality via SolidWorks and Rhinoceros tools, and the latter evaluates surface geometry via a CAD model's STL mesh data. These strategies aim to classify further mold surface geometry, where predictions can be made regarding how a flexible fabric may interact with the surface as it is placed onto it, such as where wrinkles or creases may be produced. These predictions, in turn, influence the design of the proposed gripper and how it is modified to adapt to varying mold surfaces.

3.1 Qualitative and Semi-quantitative Analysis: Evaluating mold surface via SolidWorks tools

Qualitative and semi-quantitative mold surface geometry analysis tools such as Surface Curvature Combs, Deviation analysis, color-coding Curvature Analysis, Zebra stripes tool, and Environment Map (E-Map) were previously discussed in [1] for a few typical mold surfaces using SolidWorks and Rhinoceros [7,18] by the current research group. Modification and optimization tools of surface features such as Vertical Deviation (min, max, average), Surface Smoothening, and Surface Flattening were also proved useful for removing unwanted details of the surface and wrinkle-free conformity of draping operation. These tools are briefly described and implemented on a few typical mold surfaces in the next section.

3.1.1 Surface curvature combs

Using the Surface Curvature Combs tools from SolidWorks, the type of bounding surfaces can be illustrated by the direction and magnitude of the combs. Figure 9 shows four different bounding surfaces.

3.1.2 Deviation analysis

The deviation analysis tool allows users to evaluate the angle of faces along a common edge to understand the type of continuity between those faces. Figure 10 illustrates how deviation analysis provides insight into recognizing the type of continuity between available surfaces.

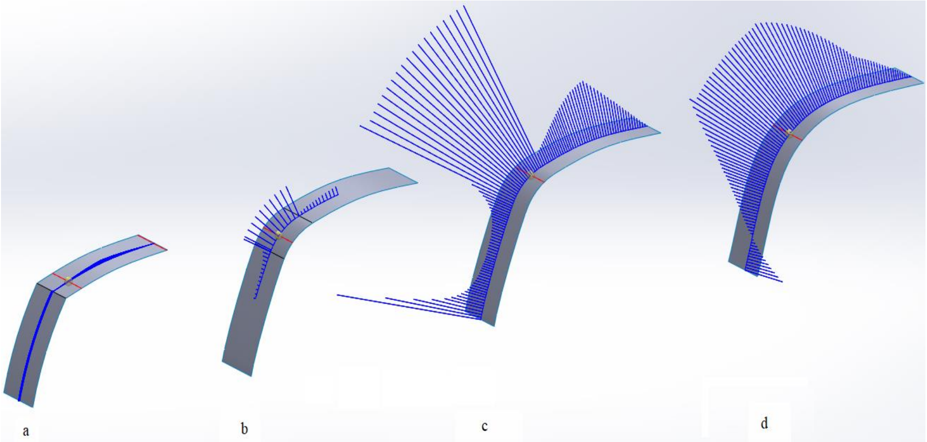


Figure 9: Four different bounding surfaces. (a) Regular Contact, (b) Tangency, (c) Tangency and Fit Spline, (d) Curvature Continuity.

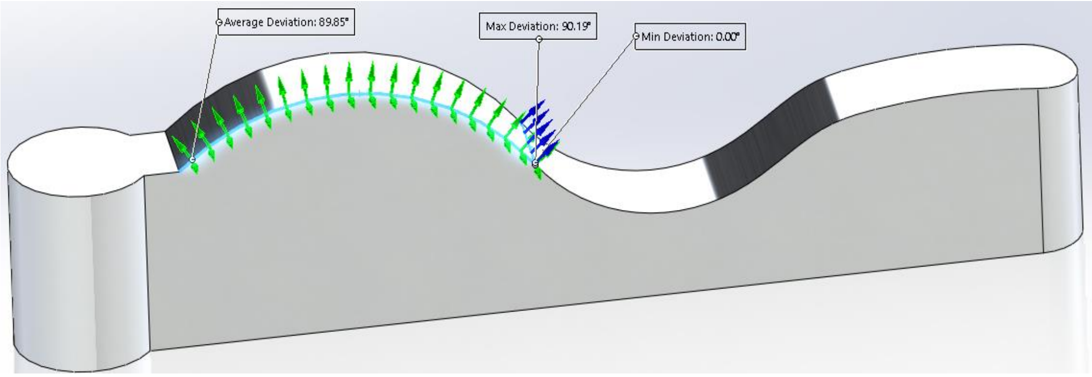


Figure 10: Deviation analysis showing minimum, average, and maximum deviation of the surface.

3.1.3 Curvature command

The curvature command is a qualitative color-coding approach in which faces are colored according to their curvature values, as demonstrated in Figure 11.

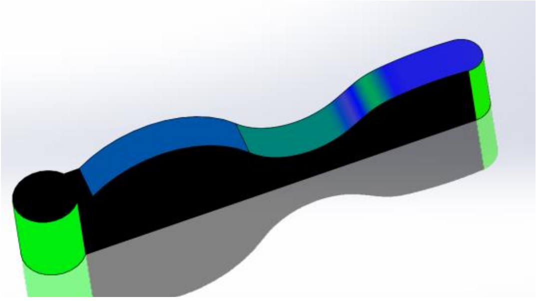


Figure 11: Using curvature command tool to demonstrate faces' curvature values.

3.1.4 Zebra stripes tool

The zebra stripes tool determines the continuity type between faces, and it works by simulating stripes of light reflecting from a surface. It looks for irregularities in both the position and the direction of the stripes, especially around edges as shown in Figure 12. Contact is an obvious misalignment in the stripes between faces. A tangency is recognized when stripes match at the boundary, but they will typically take off in another direction very abruptly. A curvature continuous is known as stripes match at the boundary. They may change direction across the edge very smoothly.

Figure 12: Zebra stripes tool for determining the continuity type between faces.

SolidWorks provides some tools for geometry analysis, as mentioned. However, additional quantified analyses, such as a curvature evaluation, as shown in Fig. 14, cannot be performed. Another tool that will assist the designer is a surface smoothness analysis (Fig. 15). Rhinoceros is used to develop these and other related advanced mold analyses.

3.2 Qualitative and Semi-quantitative Analysis: Evaluating mold surface via Rhinoceros

In Rhinoceros, users can analyze the geometry and curvature of surfaces to ensure they meet specific design requirements. The evaluation may involve checking for smoothness, continuity, or other desired attributes. Modifications can then be made to refine or optimize the surface, addressing any issues identified during the evaluation.

3.2.1 Curvature analysis

Using a curvature analysis tool allows one to detect the type of curvature and quantify the curvature value on a surface. It also enables the designer to locate and correct unacceptably sudden changes like bumps, dents, flat areas, or ripples. As a part of this evaluation tool, Gaussian and Mean analyses show if and where there are anomalies in the curvature of a surface. Figure 13 shows the curvature analysis tool applied on a typical mold surface, illustrating curvature value ranges from positive curvature (red, bowl-like) to zero (green, flat) to negative curvature (blue, saddle-like). It also generates maximum principal curvature, minimum principal curvature, and Gaussian curvature values, which are helpful in deciding if a surface can be developed into a flat pattern. Using a 'Mean curvature value helps find areas of abrupt change in the surface curvature so it can be corrected if needed.

3.2.2 Surface flattening

When it comes to draping a fabric onto a sophisticated curvy mold, there are regions in the fabric where it will be more likely exposed to wrinkles and side over-draping out of the mold borders. Therefore, it is important to cut the fabric so that it fits the shape of the mold as it is draped over for a better conformity. Surface flattening tool in Rhino performs this, as shown in Figure 14. This will be extended to develop origami inspired specialty grippers (Miura type folds), with living hinges [29].

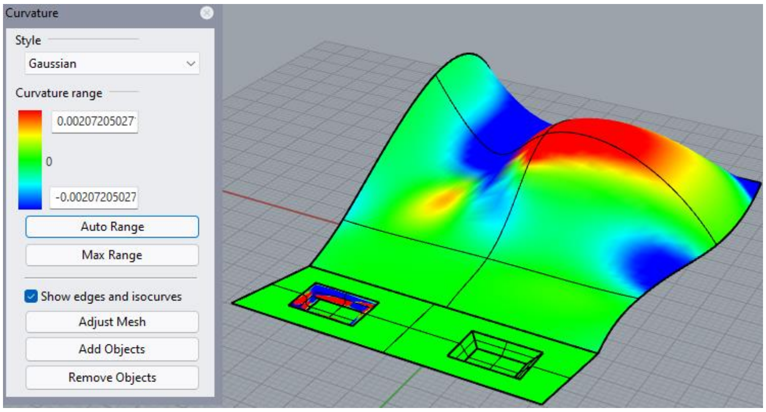


Figure 13: Gaussian analysis for understanding saddle-like, bowl-like, and flat areas.

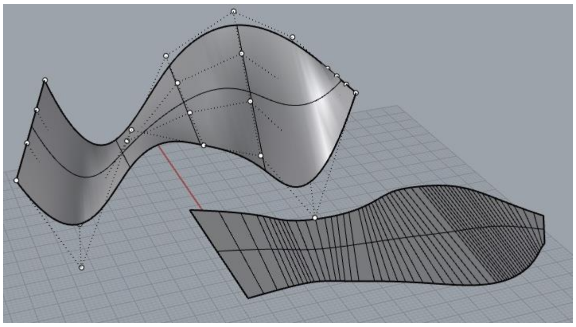


Figure 14: Mold surface flattened representing the most suitable cut for the fabric.

Although afore-mentioned qualitative and semi-quantitative mold surface geometry analysis tools as well as modification and optimization tools provide some insights towards identification, illustrative characterization and evaluation, and, prediction of mold surface regions of concern, a full quantitative methodology is essentially required for translation of characteristics of the mold surface geometry to design parameters of compliant grippers for an effective fabric material handling operation, namely, property propagation. Property propagation refers to the process of inheriting or transferring specific attributes, parameters, or properties from one component to another within a design or engineering system. Property propagation is employed to ensure consistency and efficient management of properties across different components of a system.

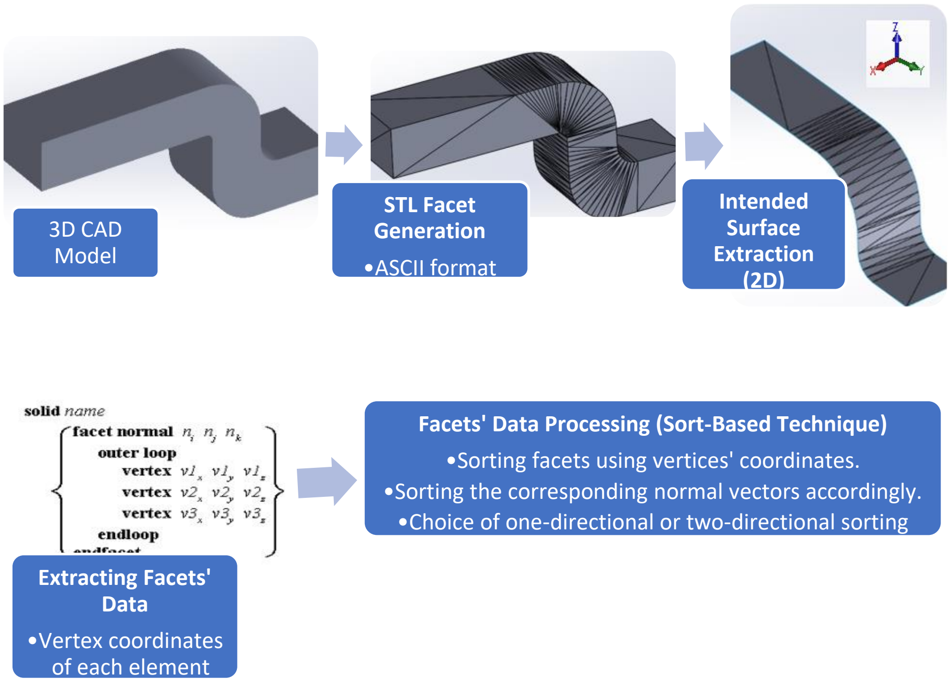
3.3 Quantitative Analysis: Evaluating mold surface geometry via STL mesh data

In this study, we have harnessed a novel technique for comprehensive evaluation and analysis of mold surface geometry features such as concavity, convexity, flatness, recessions, protrusions (bulges), fillets, chamfers, and more. This approach leverages the utilization of CAD geometry presented in the ASCII format of a surface STL file because of its faceted representation, accessibility of geometry data, and simplicity and efficiency. This simple facet-based representation in which a mesh of triangles is defined by its vertices and a unit normal vector, aligns with the way complex surfaces that can be broken down into smaller, manageable components. Each facet can be analyzed and interpreted either individually or in interaction with vicinity facet/s, making it easier to study and manipulate specific regions of a complex mold surface. Also, easy access to geometry data, including vertex coordinates and normal vectors, is essentially helpful for conducting geometric evaluations, such as angular deviation assessments.

The technique is based on a sorting approach in which facet normal vectors are treated to help classify the distinct regions within a mold and provide insights into the design of compliant grippers such that grippers can conform to any designated fabric placement area on the mold's surface. The merits of this approach for classification and analysis are shown in the case studies where a family of parts of a compliant gripper set is shown to conform to the mold surface for a wide selection of geometries. This approach uses already sorted vertices and their corresponding facet normal vector information to illustrate variations in facet normal vectors, rate of changes in facet normal vectors, and local angular deviation.

In summary, the sort-based technique involves sorting the coordinate vertices of facet triangles in different directions (x, y, or z) or combinations of directions. This sorting is done to visualize variations in facet normal vectors, which represent surface feature changes. Python programming is used to implement this technique. An alternative technique is also introduced to address sorting issues caused by shared vertices among triangles. It is named all-vertices sorting technique which involves calculating the average of all vertices coordinates in the x, y, and z directions for each triangle.

A representation of a simple s-shaped mold surface following its post-processing data processing and visualization is shown in Figure 15 to facilitate understanding the mentioned sort-based technique. The uppermost surface of the mold is the focus, and other facets are omitted to simplify the analysis. The sorting axis chosen is the Y-axis, and the data is organized based on Y-axis values, creating a sweeping appearance of the mold surface from left to right as is shown in Figure 16. Angular deviations of facet normal vectors in each pair of adjacent facets within the mold surface were analyzed to identify curvature changes. Figure 16 illustrates different regions of the S-shaped mold surface in a color-coded style along with angular deviations in facet normal vectors of corresponding regions of the S-shaped mold surface.



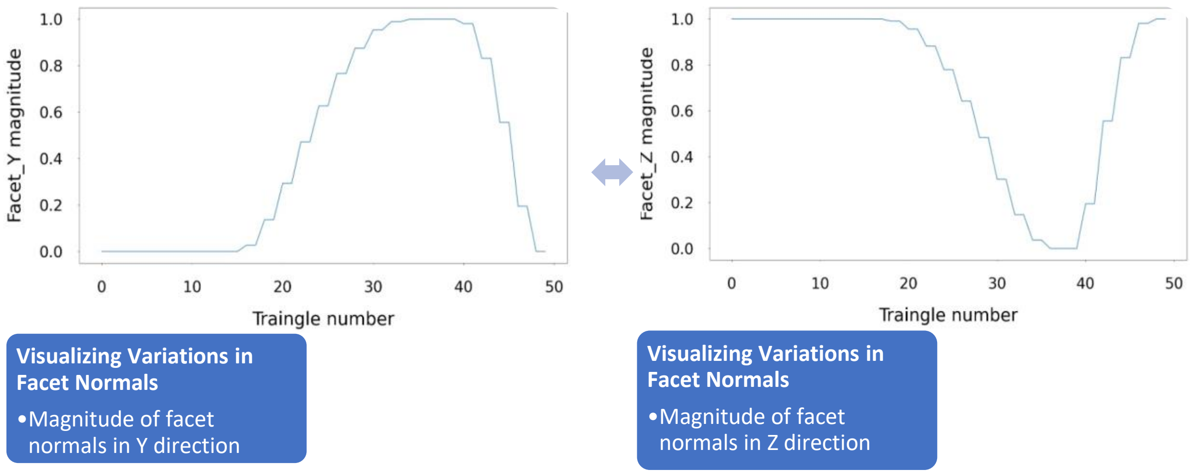


Figure 15: Implementation of the sort-based technique on a simple s-shaped mold surface following its post-processing data processing and visualization.

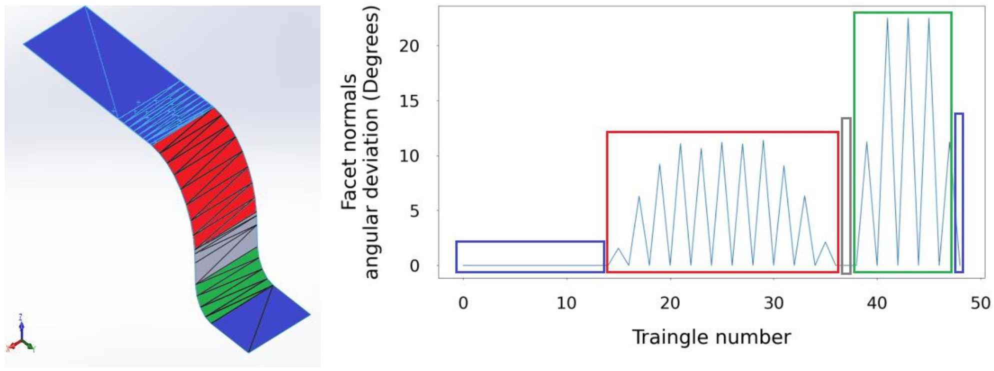


Figure 16: Color-coded regions of the S-shaped mold surface, b) Angular deviations in facet normal vectors of the corresponding regions of the S-shaped mold surface.

The pattern in Figure 16 confirms a consistent transition of surface geometry from a flat area to a curvy region. However, there is an intermittent fluctuation to zero in every other element as observed in Figure 17. This alternating return is attributed to the mesh generation methodology employed in the STL format. As illustrated in Figure 17, when a facet (1st blue facet at the left) reclines relative to its adjacent facet (left red facet), the facet next to it at the opposite side (2nd blue facet at the right) forms with the same facet normal, before the two next adjacent facets (right red facet) at the same side reclines to a new orientation.

3.3.1 Implementation of Mold Geometry Analysis Using Facet Normal Vectors

More intricate molds require sorting in two directions. In some cases, depending on the form of the facet generation, sectional sorting is useful in which each set of facets included in a section is swept first before its adjacent section. A section is a set of facets that is distinctively separated by a line or edge from other similar sections. Figure 18 demonstrates the 3D model of the composite mold and its faceted surface required for geometry analysis. This is the intended surface as it is exposed the material pick and place. Given the symmetry of the mold, one half of the top surface has been selected for simplification in evaluation.

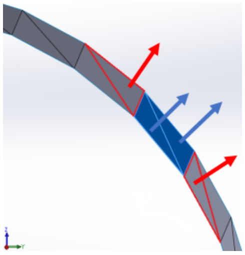


Figure 17: Facet normal vectors reclined in every other element alternately.

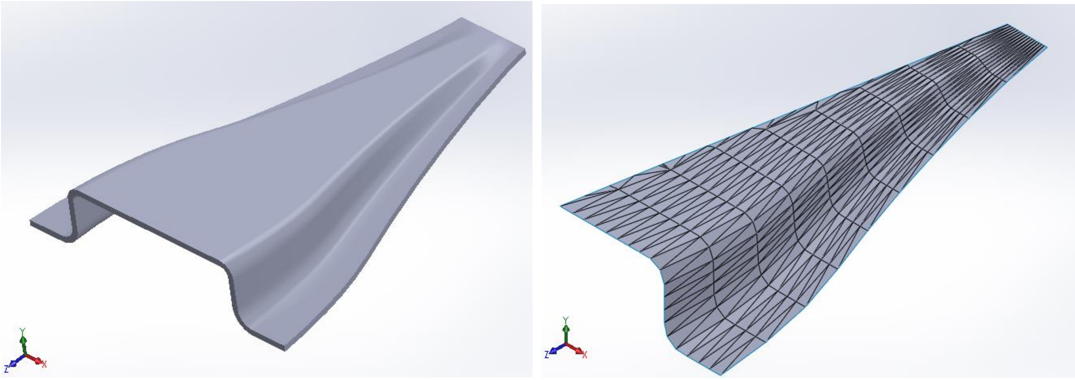


Figure 18: (a) 3D model of the composite mold, (b) Symmetric faceted surface of the mold.

As evident in Figure 19(a), the triangles are generated across nine distinct sections when sweeping the mold in opposite Z direction. Sections of the mold are examined by sorting triangles and facet normal vectors in two directions (opposite Z directions and then X direction) to analyze feature changes. This detailed analysis helps identify variations in features, facilitating the development of specific gripper design guidelines.

As previously explained for the simple S-shape mold, local angular deviation of facet normal can offer more informative and quantitative measurement criteria for gripper design. Figure 19(b) depicts the angular deviation of facet normal vectors for each pair of adjacent elements within each section of the composite mold surface using the two-directional sectional sort-based technique.

In Figure 19, we see that each section begins and ends with flat surfaces with zero angular deviation in facet normal vectors. The repetition of graphs in Figure 19 is due to the all-vertices sorting technique, but it doesn't impact result interpretation as the values are similar. Unlike the S-shape mold, the one-vertex sorting technique isn't accurate in this case due to inaccuracies stemming from jump issues, and the all-vertices sorting technique was utilized instead.

Before approaching gripper design guidelines using the provided surface analysis, a classification is required regarding non-flat mold surface regions. The variations in facet normal vectors were employed for this classification. Angular deviation of facet normal vectors of each pair of adjacent elements within the entire mold surface were utilized to classify a mold surface into three distinct regions as follows:

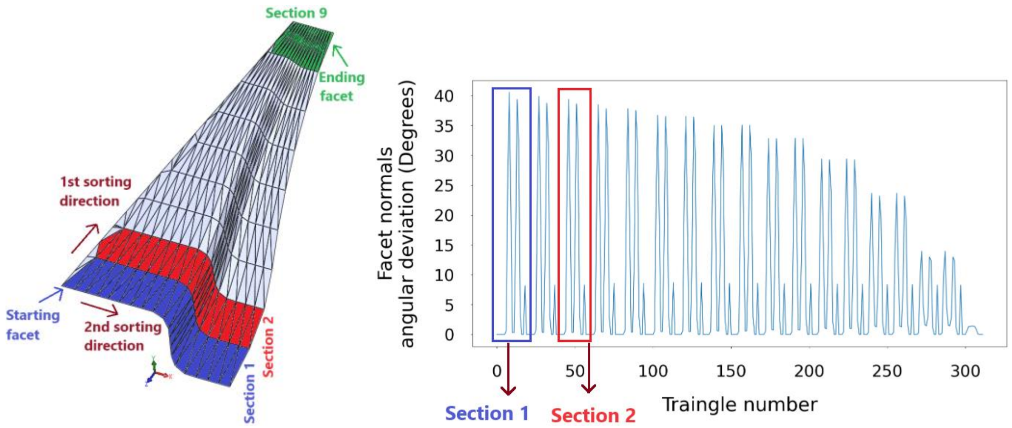


Figure 19: (a) Representation of nine distinct sections of the mold surface, (b) Angular deviation of facet normal vectors for each pair of adjacent elements within all sections of the mold surface.

- Mild region: Angular deviation of facet normal vectors of each pair of adjacent elements falls within 0 to 10 degrees.
- Moderate region: Angular deviation of facet normal vectors of each pair of adjacent elements Lies within 10 to 15 degrees.
- Steep region: Angular deviation of facet normal vectors of each pair of adjacent elements exceeds 15 degrees.

4 COMPLIANT GRIPPER-MOLD SURFACE INTERACTIVE DESIGN

In this segment, the facet-based geometry analysis technique was employed to identify the shared attributes between gripper design parameters and mold surface geometry features. This analysis aims to optimize the pick-and-place application for a seamless and efficient operation.

4.1 Functional Requirements of Compliant Grippers

The functional requirements of compliant grippers for fabric pick and place operations focus on gripping the fabric (without damage), transferring the fabric without introducing slippage [3], and placing the fabric onto different mold surfaces without wrinkling. This involves a combination of mechanical, material, robotic automation, and operational considerations to help ensure a successful implementation.

4.1.1 Miura-fold and Miura-living hinges grippers

The requirements for the Miura-fold and Miura-living hinge grippers are listed as follows:

- *Material Compatibility*

The gripper material should be compatible with the fabrics commonly used in the handling application, ensuring that it provides a reliable grip without damaging or contaminating the fabric, which may occur with adhesion grippers [2-3]. Based on experiments for a reliable grip, a minimum coefficient of friction of 0.5 is recommended between the gripper and fabric material to avoid excessive rise in grip force. This coefficient of friction needs to be determined for each set of fabric and gripper material. As an instance is discussed in an earlier study within the current research [3], where a coefficient of friction of 0.7 was determined between the woven plain carbon fabric and the soft silicon gripper.

- *Grip Force*

The gripper should generate sufficient grip force for grasping the fabric, holding it securely, and preventing any slippage during pick and place operations, while allowing for delicate handling to avoid tears or distortions. Referring to [3], using a silicon gripper with 7N of grip force, a slippage of 0.6 cm was observed in the carbon fabric when robotic gripper was moved linearly at 100 mm/s. The slippage was found 0.4 cm when 14N of grip force applied under the same test conditions, while there is no evident damage or tear introduced to the fabric material.

- *Adaptability*

The gripper should be capable of adapting to various fabric shapes, sizes, thicknesses, weave styles (Figure 1), and textures encountered in the process. This compliance also implicates gripper's conformity to different mold surface geometries (Figure 5).

- *Durability*

The gripper should be designed to withstand repetitive use over time without significant wear and tear, maintaining its gripping performance and structural integrity. Durability depends on materials used and fabrication methodology and is the subject of another study.

- *Energy consumption*

Gripper designs should prioritize minimizing energy consumption. Systems like hydraulic, vacuum, or pneumatic grippers often require a substantial and costly power source for efficient operation.

4.2 Design Guidelines of Compliant Grippers

This research places a greater focus on quantifying the varying curvature of a mold surface. This information is then used to strategically modify the design parameters of the proposed gripper, in relation to what type of surface the fabric must be placed on, (i.e. flat, non-flat or a combination of both). This is further discussed in sub-section 5.3 below. Before exploring the design guidelines for different gripper characteristics (i.e., Miura tessellation and living hinge elements), it is important to understand how the Miura gripper handles a sheet of fabric, along with a potential actuation method.

4.2.1 Fabric Handling Strategy Using the Miura Style Gripper

The Miura-Ori origami fold features a tessellation of parallelograms to create a collapsible structure [29]. The collapsible nature of this fold is useful for handling a sheet of fabric. It creates an array of small pinch points that can grip a textile's surface. Due to the deformable nature of the fabric, when force is applied in the XY plane of the Miura-Ori fold, it collapses and folds the fabric with it, creating a gentle and unique grip. A sheet of fabric can thus be grasped in multiple locations across its surface by one gripper, instead of only selected areas (i.e., if another approach was used). This is particularly useful for picking fabric sheets with cut-outs or slits. The Miura-inspired gripping strategy seen in Figure 20 is described throughout the paper as a compliant mechanism, a result of its deformable and flexible structure.

4.2.2 Potential Gripper Actuation

As previously mentioned, a force in the XY plane needs to be applied to the Miura-based gripper to collapse it. The force should be applied to two outside parallel edges of the end-effector to achieve an optimal grip on the fabric. A solution like that described in [29] would be suitable as a prototype for operating the gripper styles proposed in this paper. Figure 20 shows a hand driven, frame-like structure that allows for the gripper to be easily manipulated when attempting to pick a sheet of textile [29]. Some gripper variants discussed in the paper (Figures 27 and 30), use a combination of Miura-Ori sections and living hinges. The frame actuation strategy can be adapted for said gripper variants by using a frame sizable to the flexible end-effector. However, as this was not a focus of this paper, it is not further elaborated on.

Figure 20: Potential actuation approach for Miura-based gripper using a frame, adapted from [29].

The following summarized guidelines provide a framework for designing compliant grippers for a fabric handling operation, ensuring their compliance with different fabric shapes, materials, and mold surface geometries. The principles of the origami-inspired structures were utilized to create a gripper with inherent flexibility, adaptability, and other aforementioned advantageous characteristics.

4.2.3 Miura-fold gripper

- Use quadrilaterals to create parallelograms (Figure 21(a).
- Limit the parallelogram length to 30-50% of the end effector's closing distance.
- Avoid a thickness-to-length ratio less than 1.4% or greater than 2.8%.
- Maintain acute angles between 35-45 degrees in parallelograms.
- Apply fillets to external corners.
- Deploy parallelograms on an integrated pliable adhesive base matrix (Figure 21(b)).
- Maintain a gap distance of 12-20% between parallelograms.
- Enhance surface friction using built-in roughness fabrication methods or by adding coatings (Figure 23).
- Choose lightweight and durable materials with bending stiffness above 2.2 GPa.

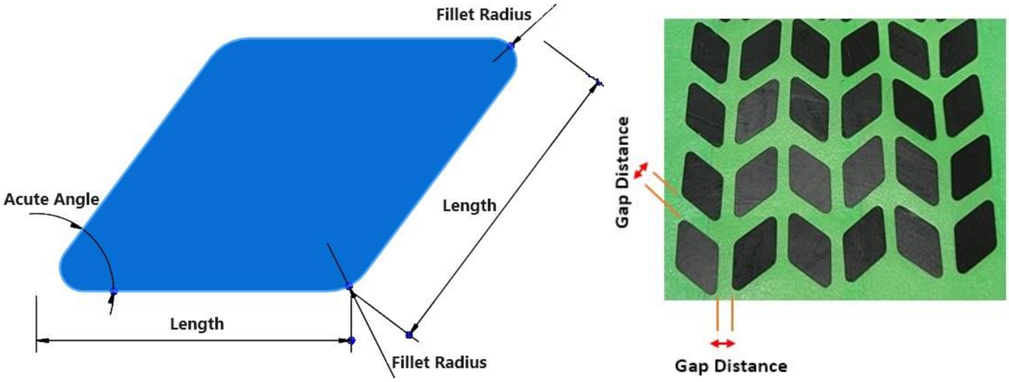


Figure 21: (a) Geometric features of a typical parallelogram, (b) Gap distance of parallelograms in paper tape base matrix.

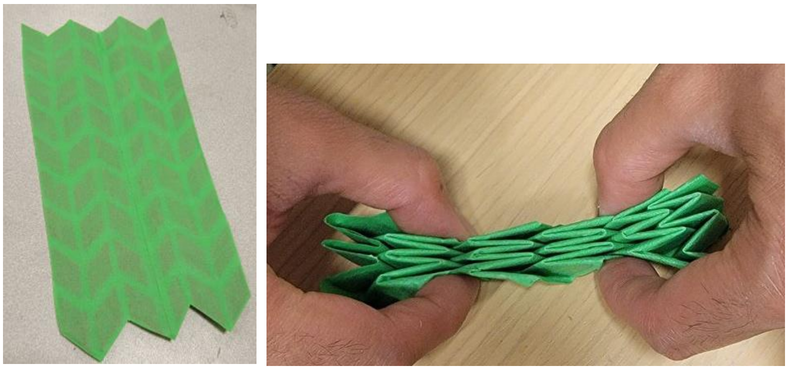


Figure 22: Different steps of deploying parallelograms in a paper tape base matrix of a Miura-fold gripper.

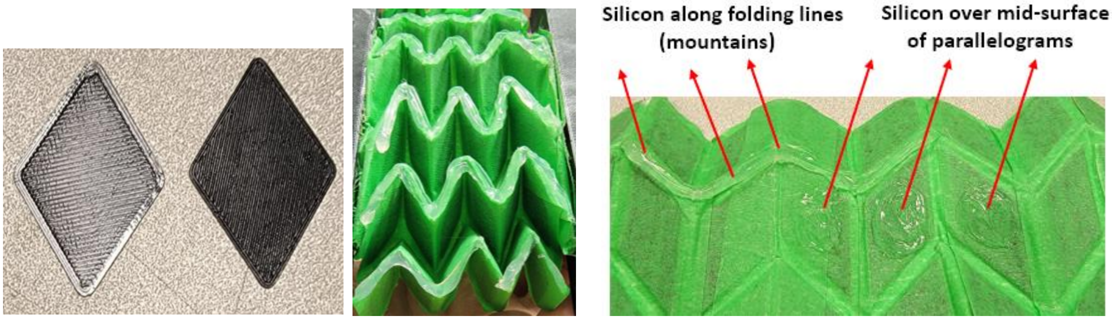


Figure 23: Surface Friction Enhancement methods: (a) 3D printed rough texture of serrated strips/dents, (b) and (c) Silicon coated on the intended area of the gripper.

4.2.4 Miura-living hinges gripper

For the Miura-Living Hinges Gripper, the same guidelines apply with slight variations.

- Use living hinges from a variety of design ideas or create a new design style (Figure 24(a).
- Limit the width of living hinges to 12-16% of parallelogram length (Figure 24(b).
- Consider the length of living hinges as 70-80% of the parallelogram's length.
- Apply grooves, slots, or gaps to the mid-region of living hinges.
- Dedicate a groove thickness to a full thickness ratio of 45-55% for living hinges.
- Apply a groove width to full-width ratio of 40%-50% for living hinges.
- Select materials with bending stiffness of 0.1-0.25 GPa for living hinges (Figure 25).

4.2.5 Ori-living hinges connector

Ori-living hinge connectors are not a type of compliant gripper but a connection/linkage that is used as flex components placed within the Miura-living hinges gripper in case bending is needed over a critical region of the mold surface (Figure 26).

- The length of Ori-living hinges connectors matches the Miura-living hinges.
- Place the connectors perpendicular to the direction of the grip force.
- The number of connectors depends on mold surface geometry.

- Limit the width of Ori-living hinges connector to 20% to 30% of the length of the parallelograms of the Miura-living hinges gripper.
- Select materials following the Miura-Living Hinges Gripper Guideline.

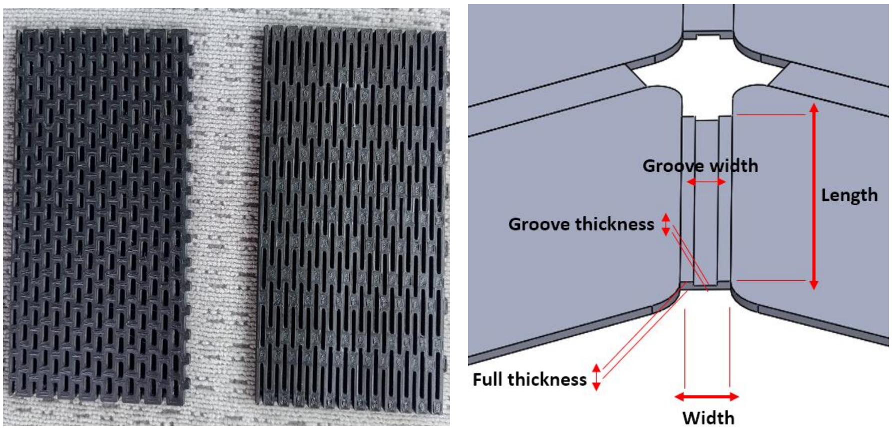


Figure 24: (a) Two different 3D printed living hinge styles [29], (b) Geometric specs of living hinge style used in the current study.

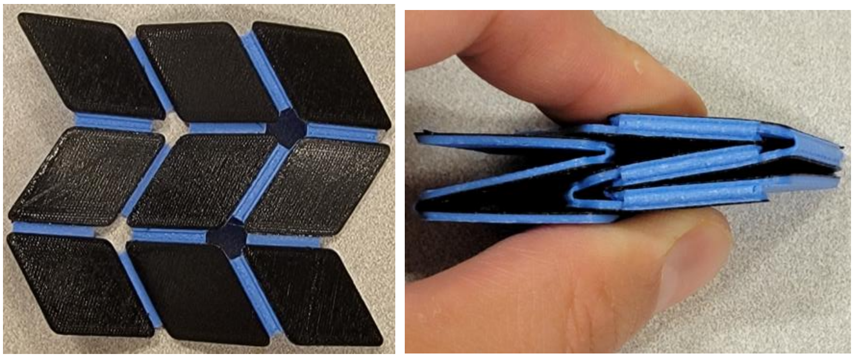


Figure 25: Miura-living hinge gripper 3D printed with a flexible 89A PLA (Sakata 3d X920).

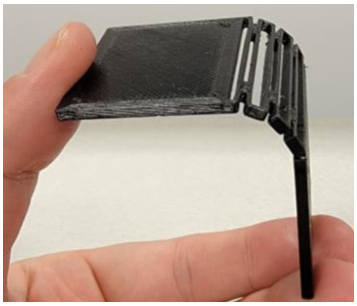


Figure 26: An Origami-based living hinge connector showcasing 90 degrees bend-over.

4.3 Design Guidelines for Compliant Gripper-Mold Surface Interaction

When designing compliant grippers, such as Miura-fold grippers or Miura-living hinges grippers, consider the following guidelines to effectively correlate gripper design parameters with changes in mold surface geometry ensuring precise and reliable fabric pick and place operation:

4.3.1 Handling operation from a flat surface to a flat surface

Use a one-dimensional accordion-like foldable gripper. Consider the length and width ratio of parallelograms and the number of parallelograms based on the fabric length and coverage.

4.3.2 Handling operation from or to a non-flat surface

- Use Miura-fold grippers for mild regions.
- Use Miura-living hinges grippers with Ori-living hinge connectors for steep regions (Figure 27).
- Adapt the parallelogram length to the critical cross-profile length. A critical cross-profile is defined as a contour/spline derived from a section cut of the mold's region of concern:
    - A parallelogram length to critical cross-profile length ratio of 3.5% to 6% is recommended in steep regions.
- Deploy Ori-living hinges connectors depending on the class of the non-flat mold region.
- Refer to specific guidelines for Miura-fold and Miura-living hinges grippers for other design parameters.

Figure 27: Two Miura-fold gripper connected with an Origami-based living hinge connector showcasing conformity over the composite mold.

5 CASE STUDIES AND DISCUSSION

To verify the effectiveness of this gripper solution approach, a set of case studies with different levels of complexities have been configured.

As illustrated in Figures 28(a), 28(b) and 28(c), three molds were designed and fabricated via AM to conduct case studies. The mold shown in Figure 28(a) is the composite mold [11]. Molds demonstrated in Figures 28(b)and 28(c)were designed in a way to adequately represent a complex of surface geometry features such as concavity, convexity, flatness, recessions, protrusions (bulges), rounded corners and contours (fillets), sharp edges and chamfers, and more.

To show the effectiveness of the implementation of compliant grippers' design parameters in relation to molds' surface geometry features, both previously discussed sort-based faceted surface geometry analysis techniques and gripper design guidelines were used in conjugation together.

Figures 28(d), 28(e) and 28(f) demonstrate corresponding faceted surface models of the typical case study molds which were used for the sort-based analysis and relationship purpose.

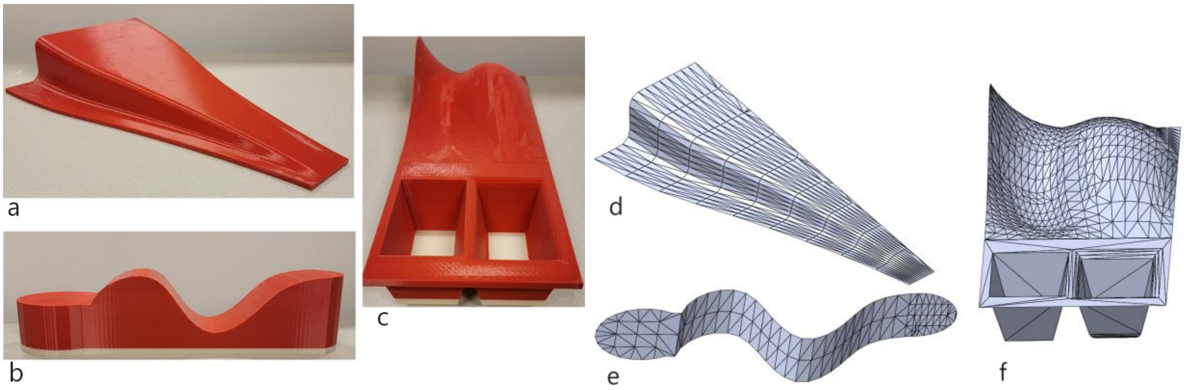


Figure 28: AM fabricated case study molds and their corresponding faceted surface models used for interactive design and analysis, (a, d) Composite mold, (b, e) Flat-curvy mold, (c, f) Pocket-curvy mold.

Figure 29 shows the faceted surface model of the flat-curvy mold and its corresponding diagram demonstrating angular deviation of the facet normal vectors of the adjacent elements within the surface. It shows two distinctive regions, which are marked with green arrows, indicating regions of the flat-curvy mold surface where the angular deviation of facet normal vectors of adjacent elements are less than 15 degrees. According to the defined classification regarding mold surface regions, this is a moderate region.

Figure 30(a) depicts two Miura-fold grippers placed on flex regions of the flat-curvy mold surface at the same location as the green arrow indicators. As is shown, Miura-fold grippers enjoy adequate adaptability and compliance to appropriately conform to the mold surface contours as desired.

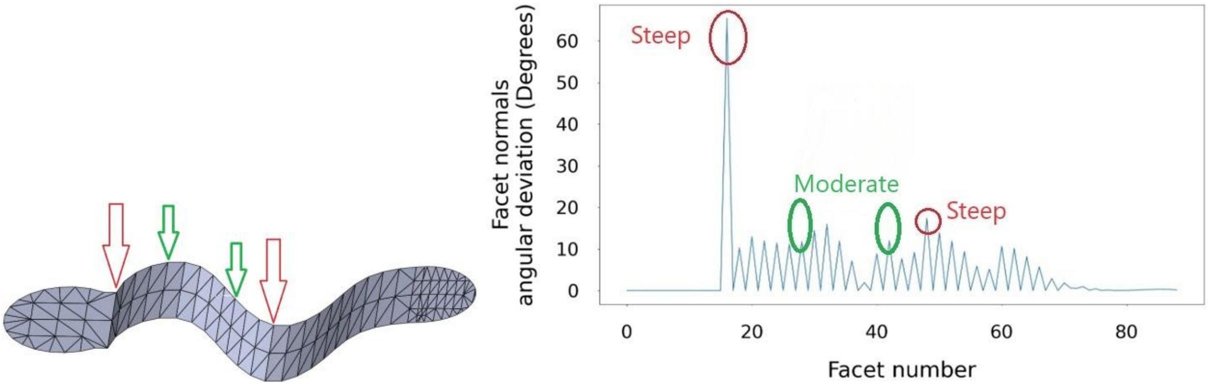


Figure 29: (a) Four different indicated regions of the faceted surface model of the flat-curvy mold, (b) Angular deviation of the facet normal vectors of adjacent elements of the flat-curvy mold surface representing the corresponding indicated regions.

On the other hand, two distinctive regions were marked with red arrows in Figure 29, indicating regions of the flat-curvy surface model where the angular deviation of facet normal vectors of adjacent elements exceeds 15 degrees. As per the defined classification of the mold surface regions, this is classified as a steep region. According to Figure 30(b) and 30(c), Miura-living hinge grippers linked with an Ori-living hinge connector show an acceptable and consistent compliancy in both steep regions since the connector component is capable of bending over those regions for a suitable conformity.

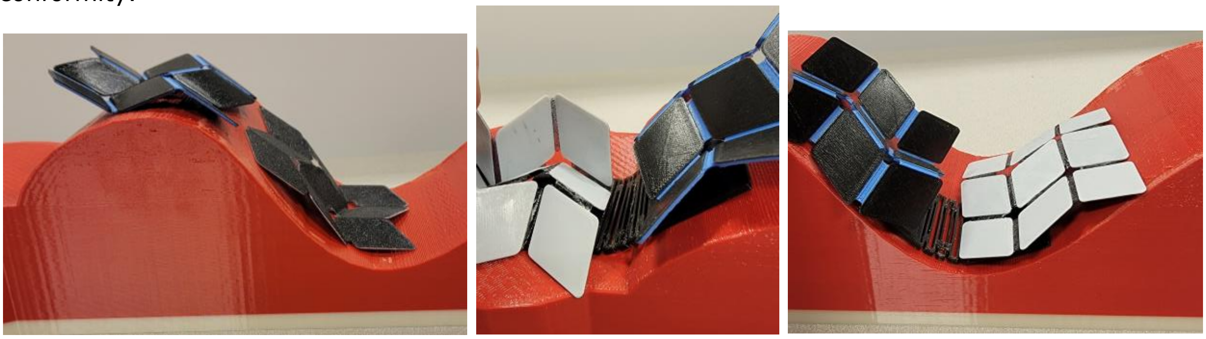


Figure 30: From left to right: (a) Miura-living hinge grippers placed over the moderate regions of the flat-curvy mold, (b, c) Miura-living hinge grippers linked with Ori-living hinge connectors adequately conformed over the steep regions of the flat-curvy mold.

Indicated steep region of the faceted surface model in the pocket-curvy mold with a sharp edge is observed in Figure 31(a). Figure 31(b) shows angular deviation of the facet normal vectors of adjacent elements of the pocket-curvy mold surface marking the corresponding indicated region of the faceted surface model. Again, this is classified as a steep region where Miura-living hinge grippers linked with an Ori-living hinge connector determined more effectively to conform to the mold surface as is shown in Figure 32.

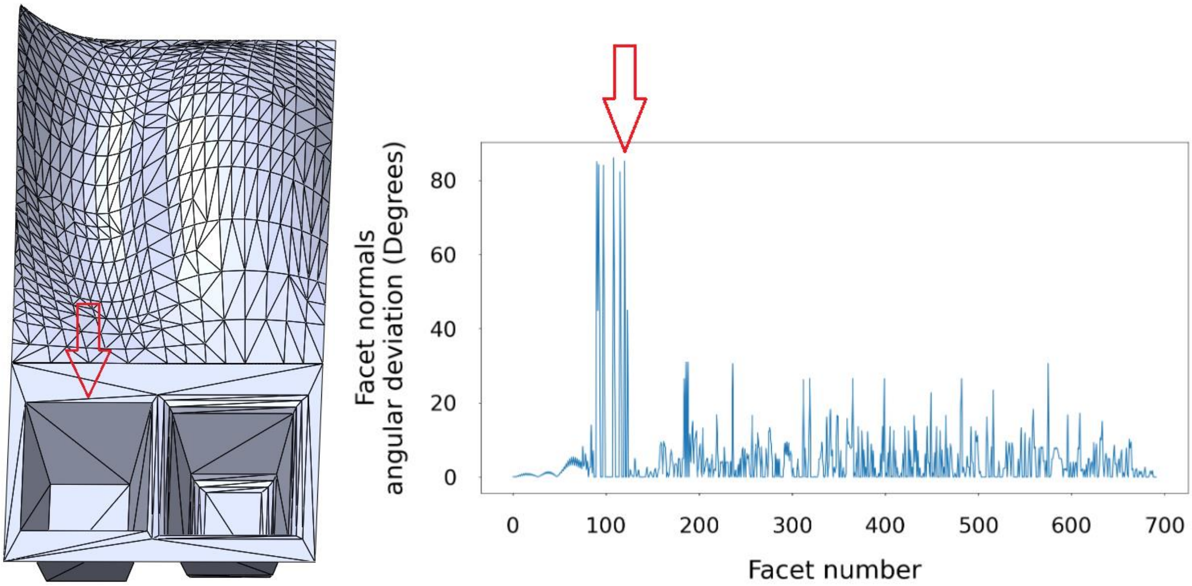


Figure 31: From left to right: (a) Indicated steep region of the faceted surface model of the pocket-curvy mold with a sharp edge, (b) Angular deviation of the facet normal vectors of adjacent elements of the pocket-curvy mold surface marking the corresponding indicated region of the surface model.

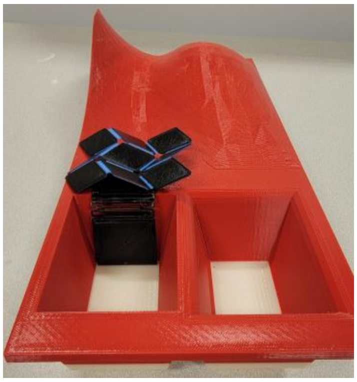


Figure 32: Compliance of Miura-living hinge grippers linked with an Ori-living hinge connector in a steep region of the pocket-curvy mold.

The presented case studies revealed that the correlation between the mold surface geometry features and the gripper design parameters works well. The sort-based technique implemented on facet surface models implies a quantitative representation of geometric changes of the mold surface. Conducting a set of different experiments with a variety of gripper design parameters and various mold surface geometry features resulted in an understanding of optimized gripper type selection and design. The classification of the mold surface regions into mild, moderate, and steep based on changes in facet normal vector of that region, and two well-established design guidelines, one merely for different compliant grippers and the other for compliant grippers in interaction with mold surface geometry features, inspired an insight into a more effective pick and place strategies when it comes to flexible material handling systems such as limp fabric handling operation.

There is still space for scrutiny and improvement, as expected. For instance, although the mold surface geometry features whose changes are quantitively represented with facet normal angular deviation can be correlated to the selection of the compliant grippers, this relationship needs more coherence and distinctness. This clarity stems from different variations in design parameters of the compliant grippers for which just one optimized variation was selected and used in this study.

Also, the interconnection between the faceted surface model and its quantitative representation of the geometric feature change (angular deviation of facet normal vectors here) has not precisely been pinpointed as it needs sweeping through the facets (considering the sorting technique implementation algorithm) from the starting facet within the surface for a marginally spotting the specific region of question or concern. This could be a limitation of this technique when dealing with highly intricate sophisticated mold surfaces.

The CAD file export format and the facet (mesh) generation algorithm used for the file export are also other factors of variability and can be seen as limitation of the presented technique. The study is based on ASCII format of the STL file exported from a CAD model. Other file export formats were not studied to check whether they provide informative model data that can be processed and altered as desired. Likewise, the mesh generation algorithm used for STL file export varies by software. SolidWorks tessellates the surfaces of 3D CAD models into a collection of triangular facets. representing the approximation of the model's curved surfaces. The accuracy of this representation depends on the specified resolution, deviation tolerance, chord height, maximum angle between two adjacent facets and adjustable refinement. Changing each of these parameters can affect the accuracy and effectiveness of the sort-based technique presented in this study and needs further investigation [7].

In the latter it is assumed that the CAD file of the mold used for fabric material handling is available and accessible. In case there is a need for reverse engineering to acquire a CAD model derived from an already existing mold, another variable parameter needs to be considered, which depends on the accuracy of the resultant derived CAD file.

The application of qualitative geometry analysis tools studied in this research contributes to the smoother management of potentially problematic mold regions and provides insights into fabric draping issues, which can be addressed during the design phase.

It was shown that origami-inspired solutions introduce a novel compliant design that boasts several advantages. They are compliant to the form of the mold contour, scalable (extendable), compact and lightweight, implicating a low power consumption, and simple in design and manufacturing. Also, they operate silently, employing a simple mechanical mechanism with easy system integration. These characteristics make them a highly promising addition to the field of automation of flexible materials handling and robotics, particularly for tasks involving material handling on complex molds surface geometries.

On the other side, while AM offers advantages like flexibility in design and quick prototyping, it has its drawbacks, such as limited loading cycles of compliant grippers due to inconsistency in fabrication, including discrete layering, tool path constraints, and existing voids and gaps. Compliant grippers often involve living hinges or flexible components and can undergo wear and tear over time, leading to reduced longevity and reliability.

In overall, the development of compliant grippers in relationship with mold surface geometry for fabric material handling applications presents a promising avenue, yet challenges remain in place to be addressed in future works focusing on systems-based approach. Upcoming works will consider fabric material variations as an important factor in enhancing grippers design and development, devising more effective pick and place strategies, tackling the limitations of grippers' fabrication methods, and discovering new analytical techniques tailored for mold surface geometry evaluation.

6 CONCLUSIONS

In this study, a comprehensive investigation into the interactive translation of mold surface geometry features to compliant gripper's design parameters for fabric material handling applications was presented. The research has culminated in a component-based approach that integrates mold surface characteristics with gripper design parameters to enable precise and reliable fabric pick and place operations. Through a series of case studies, the effectiveness of the methodology in configuring compliant grippers tailored to different mold surface geometries was demonstrated. Specifically, the successful implementation of Miura-fold grippers for surfaces with angular deviation of facet normal vectors less than 15 degrees was highlighted. These grippers have been proven to conform seamlessly to mold surface contours, ensuring accurate and wrinkle-free fabric placement. Moreover, for mold surfaces with more substantial angular deviations exceeding 15 degrees, Miura-living hinge grippers linked with Ori-living hinge connectors were introduced. These grippers have exhibited remarkable compliance, bending over sharp edges and steep flex regions, thus providing a high level of flexibility and conformity to complex mold surface features. In summary, the data processing technique applied to the facet-based representation of mold surface geometries provided the foundation for the design of specialized compliant grippers capable of seamlessly adapting to the mold's shape, ensuring a wrinkle-free placement during pick-and-place operations. This research indicates that novel compliant mechanisms can open new material handling avenues for flexible fabrics.

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