Development of a Thickness Accommodation Technique for Origami-Inspired Design

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Development of a Thickness Accommodation Technique for Origami-Inspired Design

Bryce J. Edmondson

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Master of Science

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ABSTRACT

Development of a Thickness Accommodation Technique for Origami-Inspired Design

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Designers are constantly searching for new sourcing of inspiration for innovative design. Recently, origami has gained interest as one of these potential sources. Origami literally translated from Japanese means “paper folding” where “oru” means “to fold” and “kami” means “paper”. Since paper is insufficient to solve many engineering design problems, designers must turn to other materials. These materials will inevitably be thicker than paper and will often require different folding techniques and considerations. This thesis provides background information describing previous methods to accommodate thickness in origami-inspired design, presents a newly developed technique to address limitations of other methods, and explores the application of the technique.

The newly developed technique allows designers to identify a desired motion behavior in an origami model and implement it into a thick mechanism. Many previous methods were incapable of preserving the kinematics and/or restricted usable range of motion. Understanding the capabilities and limitations of thickness accommodation methods empowers designers to better implement inspiration from origami into engineering design.

The offset panel technique is further extended to include arbitrary thickness and arbitrary folding plane locations. The technique is verified through creation and testing of hardware, showcasing capabilities and limitations. Demonstration of these capabilities will serve as inspiration for furthering application of thick origami in engineering design.

Preliminary work in thick origami led to the design of a thick origami-inspired medical gripper. These origami-inspired forceps, Oriceps, were designed by starting with an origami model exhibiting desired motion, grasping. The Oriceps show some challenges faced with accommodating thickness in adapting an origami model for application.

Keywords: origami, offset panels, rigid foldable, thickness accommodation
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CHAPTER 1. INTRODUCTION

1.1 Motivation

Thickness Accommodation in origami-inspired design is an under-explored developing area of design. There exists few methods to enable folding in thick materials. These methods however have restrictive limitations inhibiting utilization of desired properties seen in origami models. Previous methods are capable of enabling folding in thick materials, some preserving range of motion with altered kinematics and others preserve kinematics with restricted range of motion. Developing a method that would preserve both the kinematics and full range of motion would address limitations and empower designers in implementing origami inspiration into engineering design.

1.2 Thesis Objective

The objective of this thesis is to develop and present a technique for accommodating material thickness in rigidly foldable origami-inspired mechanical system designs. Thickness accommodation is one of the key challenges in origami-inspired design. The new technique is based in kinematics principles utilizing the similarity between spherical mechanisms and origami folds. Implementation of the new technique will lead to innovative applications inspired by specific kinematic behavior observed in origami.

1.3 Thesis Outline

The bulk of this thesis is comprised of three papers that were written and submitted to various venues. Those venues include IDETC2014 (International Design Engineering Technical Conference), Origami6 (book publication in conjunction with 6OSME, the 6th international meet-
Chapter 2 gives a complete breakdown of previous thickness accommodation methods with their strengths and limitations. A newly developed thickness accommodation technique, referred to as “an offset panel technique,” is presented and described in full detail. This method fills the limitation gap left by other methods by preserving the kinematic behavior of the origami source model while allowing for full range of motion. Example models are walked through step by step beginning with an origami model and ending in a thick mechanism sharing the same kinematics and range of motion. This technique gives designers another tool when exploiting the well established field of origami.

Chapter 3 expands and further develops the offset panel technique established in chapter two. The capabilities, requirements, and limitations are elaborated and showcased. Further considerations when designing thick origami-inspired mechanisms are presented to better assist in making design decisions. Application of this technique is discussed with possible implementation explored.

Chapter 4 presents the design of the Oriceps, origami-inspired forceps. The Oriceps were designed based on an origami model, Shafer’s Chomper, that exhibited a desired chomping motion. This chapter serves to illustrate the design process of utilizing a desired motion observed in an origami model as well as to show some of the challenges in thickness accommodation in design of origami-inspired mechanical systems.

The concluding chapter of this thesis provides a final summary and remarks on origami-inspired design thickness accommodation techniques.
CHAPTER 2. AN OFFSET PANEL TECHNIQUE FOR THICK RIGIDLY FOLDABLE ORIGAMI

A technique for thickness accommodation in origami-inspired mechanism design is introduced. Mathematically, origami panels are generally assumed to be planar with zero thickness. Origami models can be viewed as kinematic mechanisms where folds are revolute joints and panels are links. An origami-inspired mechanism can achieve the same kinematic motion as the paper origami source model if all joints lie along the folds in the zero-thickness plane. The panels are stacked in sequence in the closed (stowed) position. A joint plane is chosen and each panel is given extensions connecting each panel to the chosen plane. The extensions from the stacked panels allow each panel to be rigidly connected to its revolute joint in the chosen plane with all other joints. The accommodation technique utilizes origami models that are rigidly foldable. The height of the extensions are determined by the sum of the thicknesses of all panels between its stowed panel and the chosen joint plane. Any panel thickness can be accommodated, including multiple panel thicknesses within the same mechanism. Process steps for offset panel design of origami-inspired mechanisms are presented.¹

2.1 Introduction

The objective of this paper is to present and illustrate a novel technique for accommodating material thickness in flat-foldable origami-inspired mechanism designs. The typical origami material is paper that is idealized as having zero thickness. Origami-inspired applications, however, often require materials with significant thickness to meet requirements of their design. Accommodating thick materials is one of the key challenges in origami-inspired design.

¹This chapter has been accepted for publication in the proceedings of the International Design Engineering Technical Conference 2014 entitled “An Offset Panel Technique for Thick Rigidly Foldable Origami”(DETC2014-35606) [2]. Co-authors include Spencer P. Magleby, Larry L. Howell, and Robert J. Lang.
When folding paper, a common card-stock paper could be considered “thick” and tissue paper considered thin. Mathematically, origami is often modeled assuming ideal zero-thickness panels. Mechanical designs require finite thickness for stiffness and other design considerations and panels cannot often be assumed to have zero-thickness. Tachi defines thick panels as “composite three-dimensional structures with finite volume;” [3] that definition is adopted here.

The proposed technique maintains the specific kinematics of the origami source model while accommodating any arbitrary panel thickness. When self-intersection issues are accounted for, range of motion is unhindered. Zero-thickness panels are replaced with thick panels, offset, and assembled to form a compact mechanism. Each offset panel is hinged, such that in the fully-folded state, its rotation axis remains in a common zero-thickness plane with all others. This planar commonality of rotational axes enables equivalent kinematics to the original zero-thickness origami source model while maintaining full range of motion. While our technique works for crease patterns containing vertices of arbitrarily high degree, in this paper, for simplicity, we will address only patterns containing degree-4 vertices.

2.2 Background

2.2.1 Origami

Origami has become an increasingly popular source of inspiration for engineering research. Having been practiced since the 1600s and likely even longer, origami is found within hundreds of published books. Origami is categorized many different ways, including divisions based on what the design looks like, how difficult it is to fold, how it moves, and whether or not it can be folded from rigid materials. Divisions of rigidly foldable and flat-foldable origami are of particular interest in mechanism design [3]. Rigidly foldable designs can achieve motion from an initial position to a second desired position without deflecting any panels or creating new folds. Flat-foldable designs are those which in their final folded state can be flattened into a single plane without creating any new folds. If a flat-sheet crease pattern of degree-4 vertices is flat-foldable and at least one intermediate position exists, with nonzero fold angles, then it is continuously rigidly foldable from fully flat to fully deployed with a single degree of freedom (DOF), apart from self-intersection issues [4].
Action origami is an area of origami which allows motion in the final folded state. Published action origami models [5–8] were investigated and classified according to their crease patterns that allowed for motion [9]. Of the observed models, those that were rigidly foldable with relative motion between panels were labeled kinematic origami. Kinematic origami models are good candidates for origami inspiration because of their promise for transferring into non-paper material designs.

### 2.2.2 Kinematics

Origami has been identified as a class of spherical mechanisms [10]. An ordinary origami linkage is a mechanism consisting of revolute joints where at each vertex of the structure, the revolute joints all point to a common spherical center and the angles between adjacent revolute joints around a vertex sum to 360°. This relationship is similarly seen in spherical change point mechanisms. Degree-4 vertices in origami are composed of 4 linkages that behave as a spherical four-bar. When looking at kinematic motion, the path of the joints are set and link shape can be arbitrary. If two mechanisms have the same link lengths (distance between joints) and same orientation (order), then they have equivalent motion. Therefore, even mechanisms with drastically different link shapes can be kinematically equivalent so long as the link lengths and orientation are the same. [11]

### 2.2.3 Highly Over-constrained Mechanisms

Over-constrained mechanisms may have motion over a specific range even though the Kutzbach mobility criterion calculates zero or even negative DOF. This is possible due to the coupled orientation of the mechanisms’ links. Mechanisms that are composed of highly coupled systems with many linkages and multiple couplings are therefore deemed highly over-constrained mechanisms [12,13]. These mechanisms most commonly consist of symmetric linkages or repeating patterns often in loops. The highly over-constrained nature of these mechanisms can enable complex linkage networks to be actuated with a single DOF.

Certain origami mechanisms remain one-DOF even when they are highly over-constrained. In particular, flat-foldable degree-4 vertices have the invariant of \(\tan(\gamma_i/2)/\tan(\gamma_j/2)\) where \(\gamma_i\) (\(\gamma_j\))...
is the dihedral of the \(i\)th (\(j\)th) angle for all pairs of angles \(i\) and \(j\). This property gives rise to mechanisms like the generalized Miura-ori having one DOF.

### 2.2.4 Thickness Accommodation

Origami-inspired design in thick materials require methods to alter the design that compensate for nonzero thickness. Current methods are categorized below into methods that preserve full range of motion and those that preserve kinematics of the origami source model. Methods that preserve range of motion are the axis-shift, slidable hinges, multi-level symmetric vertices/offset hinges, and membrane folds methods [1, 14–16]. The tapered panels method preserves kinematic motion [1].

The axis-shift method enables thick panels to fold by shifting the rotational axis to the top or bottom edge for a valley or a mountain fold respectively. This enables motion but its kinematics differ from the origami source model. This change has minimal impact in single vertex structures but can drastically alter highly coupled systems such as tessellations. This method is illustrated in Fig. 2.1a [1].

The slidable hinge method [14] of thickness accommodation proposes hinges that allow for sliding shear movement of adjacent panels as the fold angle increases. Trautz and Kunstler found that when origami is made of thick materials, the hinges must be allowed to translate to achieve motion. This adds a required number of constraints which if uncompensated for, require sliding shear motion along the rotational axes. This sliding deflection increases as panels are folded such that the shear motion causes separation of panels at the vertex which is unachievable in paper origami models [14]. This complex hinge behavior changes the kinematics of the origami source model and is rarely practical for physical design.

The multi-level symmetric vertices method [15] utilizes symmetry as well as two-level thickness panels. By shifting the rotational axis off center, the two-level panels are capable of one DOF motion from 0 to \(\pi\). This method works for a single degree-4 vertex in symmetric single parameter patterns (i.e. Miura-ori vertex) [15]. An addition to this method extends the hinges further away from the panels with extended hinges. This allows for fully flat deployed panels with extended hinges that can sequentially fold into a compact cubic bundle. This method changes the
kinematic motion of the origami source model. Its motion also becomes sequential with multiple DOF [15].

The membrane folds method was developed for a collapsible solar array [16]. This method applies thick materials on top of a flexible membrane. Mountain folds bend along an axis shared by bottom edges of adjacent panels. Valley folds are enabled by creating a gap equal to the sum of the adjacent panels’ thickness creating a rotational axis for each panel [16]. Membrane folds enable physical prototyping but it also alters kinematics of the zero-thickness model. The large gaps for valley folds add parasitic motion, causing stability concerns in some applications.

The tapered panels method [1] results in kinematics that are the same as the origami source model. Instead of shifting the rotational center, it alters the panels’ geometry by tapering the panels’ thickness on the top or bottom so the rotational center is held constant but is now at the edge of the tapered surface. Fig. 2.1 illustrates the difference between the axis-shift method and the tapered panel method. While the tapered panel method maintains the kinematics of the origami source model, it is limited in range of motion in that it cannot be fully collapsed into a second plane, shown in Fig. 2.1b [1].

Origami-inspired mechanism design is based on the fundamentals of origami artists’ extensive experience integrated with the fundamentals of kinematics. The proposed technique for thickness accommodation preserves motion attributes seen in origami models.
2.3 Offset Panel Technique

The proposed thickness accommodation technique uses offset panels with the key principle being to maintain the kinematic properties of the origami mechanism, as illustrated in Fig. 2.2.

The zero-thickness origami model achieves motion through bending along folds set by its crease pattern. In flat-foldable models, all of these folds begin and end in a plane. Therefore, in thick origami mechanisms, the same motion is achievable if the joints’ rotational axes all lie in a common plane along the same fold lines. This creates a virtual crease pattern on the joint plane.

Design starts with a flat-foldable crease pattern. Each panel’s thickness is chosen and then stacked in sequence in the stowed (folded) state. The plane in which all rotational axes will lay is then chosen. Since each panel is in an offset position from the joint plane, each panel requires some joint that provides rotational motion about the proper fold axis in the chosen joint plane. This may be a rigid extension with a physical joint in that axis or an alternate joint that allows a virtual center of rotation about that axis, such as is common with the pseudo-rigid-body analysis of compliant mechanisms [17]. The rotational axes must be coincident with the crease pattern folds to mimic the origami kinematics. The plane in which all of the joint axes reside is not limited to be within the panels’ thickness but could be far offset from the planar layers, which has the effect of increasing the relative offset in the deployed form.
2.3.1 Source Model Attributes

The following attributes are important when accommodating thickness using this technique.

**Rigidly/Flat-foldable:** The origami source model should be rigidly foldable. For the basic degree-4 vertex (spherical linkage) the relationships between sector angles and dihedral angles can be analyzed analytically. Let $\gamma_i$ be the dihedral angles. Only for the special case of a flat-foldable vertex does $\tan(\gamma_i/2) = c_i \times x$, where $c_i$ is a fixed constant for each dihedral angle and $x$ is a varying measure of the “degree of openness” of the vertex [4]. This shows that for any network of flat-foldable degree-4 vertices, if the relations between the $\gamma_i$’s are met at any one nonzero $x$ (at any partial angle), the same relations hold at all intermediate angles, meaning the structure is rigidly foldable from fully closed to fully open (not including self-intersection issues). Designing highly over-constrained mechanisms that have a single DOF is enabled by using a flat-foldable crease pattern.

**Sortable:** The origami source model should be sortable in order to use planar panels with finite thickness. All panels should be stacked in specific sequence offset from a common joint plane (sortable). The crease pattern is sortable if all panels can be ordered without any one panel occupying non-adjacent planes. If the panels are constant-thickness and oriented parallel to the joint plane, the crease pattern must be sortable. We note that if we allow tilted or non-planar panels, non-sortable patterns may be used.

2.3.2 Process Steps

This thickness accommodation technique is outlined in steps taken to design a thick origami mechanism. Along with the process steps two example thick origami mechanisms will be referenced for context. Example 1 will be a chain of four uncoupled hinged panels similar to the other method illustrations in Fig. 2.1. Example 2 will be a well known square twist pattern with mountain-mountain-valley-valley center panel fold orientation.

**Step 1. Model Selection** Select an origami source model that meets the above requirements of being rigidly/flat-foldable and sortable. **Example 1:** The simply hinged panels are uncoupled
Figure 2.3: A chain of four panels accordion folded. a). Zero-thickness model b). Offset panels model with joint plane located on bottom surface of the center panels

Figure 2.4: A square twist crease pattern used as an origami source model to illustrate the offset panel thickness accommodation technique. The panels are labeled according to their sorted sequence from the joint plane. The joint alignment marks and notches are also added to the crease pattern (shown along the folds.)

and rigidly foldable. The crease pattern is shown in Fig. 2.3a. Example 2: The MMVV square twist crease pattern shown in Fig. 2.4 is rigidly foldable and sortable.
Figure 2.5: Depending on the panel order and separation, the joint placement varies. This side view shows possible placement options with panel/joint relations. In each case the panel on the left is stationary and the panel on the right is mobile. The solid lines show the stowed position while the dotted lines show open position. Black dots indicate rotational axis of joint. The first six cases (A’s and B’s) are special cases for when the joint plane lies on panel 0’s top surface (panel 1’s bottom). The last three are general cases (C and D’s) where the joint plane lies offset from both panels n and m (n and m are the sorted panel numbers determined by their relative position to the joint plane.)

**Step 2. Place Joint Plane** Determine the location for the joint plane to be placed. It can lay on one of the panel surfaces or on a virtual plane offset from all panels. Example 1: The bottom surface of the unfolded panels is the chosen joint plane. Example 2: The joint plane for the MMVV square twist was chosen to be the top surface of the center panel in the 3x3 array.

**Step 3. Sort Panels** Each panel is ordered according to its stowed (folded) location. A paper model aids in determining the layer stacking. Example 1: The joint plane lies in the center of the 4 panels with 2 on top and bottom. Example 2: Fig. 2.4 labels the order of the example mechanism.

**Step 4. Thicken Panels** Panel thickness is chosen/determined; certain applications may require different panels to have different thicknesses. Example 1: All 4 panels were chosen to be the same thickness to match the previous methods’ figure. Example 2: Uniform panel thickness of $\frac{1}{8}$ inch was used.

**Step 5. Offset Panels** Stack the thick panels according to the sequence determined in step 3. Example 1: The first step of Fig. 2.3b shows a side of the stacked panels. Example 2: The thick panels are offset in the sequence found in step 3.
Figure 2.6: This top view of deployed panels show whether the extension should lie inside the panel edge or outside the panel edge. The cases shown in Fig. 2.5 correspond to these placement cases. The vertical lines indicate adjacent panel edges for each case. Extensions that lie inside the panel edge are located in notches (shaded gray). Extensions that lie outside the the panel edge should be located with alignment marks.

**Step 6. Determine Extensions**  Select the type of joint that will be used to connect adjacent panels such that panels achieve rotational motion about the respective fold axis in the joint plane.  

*Example 1&2:* The method used for the examples is to rigidly attach an extension, with height equal to the distance from the offset panel to the joint plane. Fig. 2.5 shows the extension placement between adjacent panels.

**Step 6a. Extension Alignment** Fig. 2.5 shows a key to the extension placement between two panels. The generalized placement shown with $n$’s and $m$’s are valid for any joint plane but the numbered orientations (0,1,2) are special cases for when the joint plane lies on a surface of a panel. All extensions connected to a single panel will be equal length since all panels are parallel to the joint plane.

**Step 6b. Extension Positions** The placement of extensions is determined by the position of adjacent panels in the stowed position, with the extension usually lying on the inside or the outside of the panel’s edge. These placements are outlined in Fig. 2.6 to ensure the joints’ rotational axis falls on the respective virtual crease pattern fold.  

*Example 2:* Fig. 2.4 shows the panels connections with alignment marks and notches.

**Step 7. Panel Connections** Adjacent panels are hinged together in the orientations determined in step 6.  

*Example 1&2:* Each adjacent panel extensions are connected with a living hinge. (in Example2’s case, a flexible fabric tape).
Figure 2.7: Clearance holes for the sample joint between panels -4 and -3 are illustrated. The clearance boundary is drawn around the joint shown as a dashed box. The sample joint needs access through panels -2, -1 and 0. The box is reflected to each target panel shown with curved arrows about the fold line it crosses. Reflected holes that fall outside the target panels’ boundary, as shown by the dashed box outside panel -2’s boundary, can be ignored.

**Step 8. Add Clearance Holes** Any panel that exists in the path between a joint and the joint plane will need holes cut to allow access for each extension.

**Step 8a. Identify Panels** Identify all joints that require clearance holes to access the joint plane and which panels each joint must pass through. *Example 1:* No clearance holes are necessary for the accordion folded 4 panels. *Example 2:* The MMVV square twist has 5 panels that block joint plane access to 3 joints.

**Step 8b. Reflect Clearance Holes** Clearance holes are located in the deployed position by sketching the clearance boundary around a joint and reflecting it across the fold line between that joint and the target panel requiring the clearance hole. Note that this technique ensures clearance in the stowed and deployed positions. Ensuring no self intersection through full range of motion requires more complex algorithms to map panel volumes through entire motion.*Example 1:* No clearance holes. *Example 2:* Fig. 2.7 shows the reflection steps, shown by arrows, to locate clearance holes for a sample joint. The fold line between the joint and target panel is used as the reflection line. Any
Figure 2.8: A square twist crease pattern with necessary clearance holes. The different colored boxes indicate clearance holes with each color corresponding to a different joint.

hole that falls outside the target panel boundary following reflection can be ignored.

Fig. 2.8 shows the cut pattern that includes all clearance holes.

Step 9. Construct Design The extensions and panels, with appropriate clearance holes and locations for extensions are manufactured and assembled. Example 1: The basic 4 panel accordion chain made using this technique is illustrated in Fig. 2.3. Example 2: The MMVV square twist was constructed using the technique is shown in open (Fig. 2.9), midway (Fig. 2.10), and closed (Fig. 2.11) positions. The MMVV square twist was made with 1/8 inch medium density fiberboard cut using a laser cutter.

The mechanism is now complete and will have the same kinematics as the origami source model.

When modelling origami using the offset panels technique, the following recommendations should be considered to simplify the design process and ensure best results.

- Use Physical Models: Fold a paper version of the chosen model to aid in visualizing the thick mechanism.
• Minimize Overlap: Crease patterns with less overlap in the folded state will require fewer clearance holes. Note that clearance holes can be further minimized with judicious choice of the joint plane location.

• Label All Parts: Labels on each part facilitates assembly.

2.3.3 Example

The following example was designed and prototyped using the described technique for thickness accommodation. It serves as an additional proof of concept and visualization of the technique.

Miura-ori tessellation The Miura-ori tessellation is a well-known origami model that is flat-foldable and rigidly foldable (crease pattern shown in Fig. 2.12). A Miura-ori model constructed using the technique is shown in open (Fig. 2.13), midway (Fig. 2.14), and closed (Fig. 2.15) positions. The joint plane was chosen to be the top surface of the center panel. In the closed position, there are 4 panels above the joint plane and 5 below. Its overlapped folds condition requires careful joint placement but few internal panel clearance holes.

2.4 Conclusions

The following have been identified as advantages of the orthogonal construction technique over other methods when designing for origami inspiration and preserving kinematics.

• The origami model’s kinematics is maintained.

• Arbitrary panel thickness can be accommodated while maintaining the motion of the origami source model.

• The panels are stacked in closed position so the construction is orthogonal.

In implementing the offset panels technique the following issues required consideration.

• It may be necessary to add clearance holes in some layers to avoid mechanical interference.
Figure 2.9: Open mountain-mountain-valley-valley square twist

Figure 2.10: Partially open mountain-mountain-valley-valley square twist

Figure 2.11: Closed mountain-mountain-valley-valley square twist
In the deployed state, the different panels end at different levels (the deployed panels are not in a single plane).

For many applications, such as solar arrays, these issues can be accommodated. This technique has been demonstrated with degree-4 vertex mechanisms enabling smooth single DOF motion kinematically equivalent to a zero-thickness source model. It allows for any panel thickness to be accommodated. It maintains kinematic equivalence by ensuring all joint rotational axes are along the folds in a plane creating a virtual crease pattern.

2.5 Acknowledgment

This work is funded by The National Science Foundation and the Air Force Office of Scientific Research under Grant No. 1240417.
Figure 2.12: Miura-ori tessellation crease pattern

Figure 2.13: Open Miura-ori tessellation

Figure 2.14: Partially open Miura-ori tessellation

Figure 2.15: Closed Miura-ori tessellation
CHAPTER 3. THICK RIGIDLY FOLDABLE STRUCTURES REALIZED BY AN OFFSET PANEL TECHNIQUE

The offset panel technique accommodates non-zero thickness to create origami-like motions with thick materials. It preserves the kinematics of the origami source model independently of the panel thickness, gaps between panels, or planarity of panels. The new methods are described and verified in hardware. Morphable volumes using this method are presented.¹

3.1 Introduction

Rigid-panel origami is often mathematically modeled with idealized zero-thickness panels. When paper is used to realize an origami design, the zero-thickness models are a good approximation. However, many origami-inspired designs require the use of thicker materials that likely will not behave as the zero-thickness kinematic models predict.

The offset panel technique [2] maintains the kinematics of a zero-thickness origami source model over its full range of motion. The offset panel technique accommodates uniform and varying panel thickness as well as offset panels or gaps between panels. The preserved kinematic behavior allows designers to select an origami model based on desired motion and instantiate it in thick materials.

In this work, we present the offset panel technique along with its capabilities and limitations and several hardware demonstrations. The examples in the paper are based on the rigidly foldable M3V twist² shown in Figure 3.1. This twist tessellation was developed using the method of fold-angle multipliers [19].

¹This chapter has been submitted for publication in the Origami6 book in conjunction with the 6th International Meeting on Origami in Science, Mathematics and Education (6OSME) entitled “Thick Rigidly Foldable Structures Realized by an Offset Panel Technique” [18]. Co-authors include Robert J. Lang, Michael R Morgan, Spencer P. Magleby, and Larry L. Howell.

²“M3V” (or $M^3V$) refers to the crease assignment around the central polygon of the structure: three mountains and one valley fold.
Figure 3.1: This origami model is a unit from a M3V twist tessellation. (a) Crease pattern (b) Open position (c) Mid position (d) Closed position

### 3.2 Background

#### 3.2.1 Action Origami

Action origami is a subset of origami of special interest because its mechanisms can be applied to engineering problems. In action origami, some models require deformation of their panels to enable action, one example being the traditional flapping bird [5–8]. Others achieve their motion purely through rotation about the folds without the bending of panels. Such models are called “rigidly foldable origami” or “kinematic origami” [9].

#### 3.2.2 Modeling and Kinematics

Kinematic origami may be modeled as a network of spherical mechanisms where panels are links and folds are joints [20] and can be analyzed using spherical kinematics theory. Each vertex within the structure is modeled as a spherical kinematic mechanism. Spherical kinematics is a subset of 3-dimensional kinematics where any given point on the mechanism is constrained to move on a spherical surface and all joint axes, whether fixed or instantaneous, intersect at the spherical center. Spherical kinematic motion is the behavior of the rotational axes about the spherical center [21, 22]. The spherical kinematics of a model can be preserved as long as the rotational axes’ locations and behaviors remain constant even if link size, shape, or both are altered.
3.2.3 Deployable Structures

One potential area of application for origami-inspired design is deployable structures. Deployable structures often use a repeating pattern of coupled mechanisms [23], such as the Bricard linkage [24] or the Bennett linkage [25] to create large single-degree-of-freedom (DOF) mechanisms. Deployable structures are often classified as highly over-constrained mechanisms because the Kutzbach criterion would calculate zero (or negative) DOF, yet they have one DOF due their highly coupled construction [12, 13].

3.2.4 Thickness Accommodation

In engineering applications of origami-inspired design, accommodation of material thickness is frequently necessary to achieve the design’s objective. Existing methods for thickness accommodation can be grouped into two categories: first, methods that preserve range of motion, and second, methods that preserve kinematics. Figure 3.2 shows a side-by-side illustration of some of the methods described below using a simple four-panel accordion fold.

The axis-shift method [1] maintains the range of motion of an origami source model. This method allows the panels to fold by shifting all joints’ rotational axes from the center plane to the panel edges (see Figure 3.2b). Interior degree-4 vertices fold such that there are 2 inside and 2 outside panels. The inside panels fit within the outside panels in thin materials but not in thick materials. A drawback is that in many origami patterns of interest, the vertical offsets break the kinematic motion of the individual vertices.

The offset joint method [15] is related to the axis shift method in that each hinge is positioned at the edge of the material. The panels are not restricted to be planar, coplanar, or uniform thickness. By extending the hinges away from the panels, gaps are created to allow interior vertices full range of motion, tucking the inside panel into the gap created by the offset. Fully compact cubic bundles were created using this method that can fold and unfold sequentially rather than with preserved kinematics. By utilizing symmetric single parameter vertices, single-DOF mechanisms can be created in thick material using this method.

In the membrane folds method [16], all rigid panels are attached to one side of a flexible membrane as shown in Figure 3.2c. By controlling the spacing between adjacent panels, full
Figure 3.2: (a) The zero-thickness model describes the fundamental kinematic behavior. (b) The axis-shift alters the kinematics but can be folded fully compact. (c) The membrane folds method alters the kinematics but can be folded fully compact. (d) The tapered panels method with limited range of motion. (e) The offset panel technique has the same kinematics as the zero-thickness model and has full range of motion.
range of motion folding is enabled. Zero gap between panels only allows a mountain fold where a larger gap is necessary for a valley fold with gap width set by panel thicknesses and desired max rotational angle. This gap also provides extra DOFs with small additional motions that can allow a theoretically non-rigidly foldable structure to fold up in practice, however, it can permit undesirable (and unpredictable) additional motions in the deployment.

The tapered panel method [1] is designed to preserve origami source model kinematics. The panels are trimmed until the panel edges are coincident with the plane defined by the zero-thickness model (see Figure 3.2d). Because the rotational axes are unchanged, the thick panels’ kinematics are equivalent to that of the zero-thickness model. The tapered panel technique, however, yields models that may not be foldable to a fully compact state, and typically do not achieve the full range of motion of the zero-thickness model.

The offset panel technique [2] can preserve the kinematics and full range of motion of the origami source mechanism, thus enabling origami-inspired designs to more closely mimic properties identified in zero-thickness models (see Figure 3.2e).

3.3 Offset Panel Technique

In rigid origami, panels (facets) can be treated as links and folds as joints [26–28]. Origami mechanisms can be treated as zero-thickness spherical mechanisms, which are mechanisms whose links and joints all lie in a plane in at least one position and whose links are idealized with zero-thickness. In the offset panel technique, the source model’s panels are shaped and thickened while maintaining the zero-thickness spherical mechanisms’ joint relationships.

The key concept of the technique is that in the fully folded state, all joints lie in a common plane even if one or both panels incident to any joint are spatially offset from that plane, which we refer to as the joint plane. This requirement allows the thick origami mechanism’s behavior to be kinematically equivalent to the zero-thickness origami source model, aside from considerations of self-intersections, which must be addressed separately. We accomplish this requirement by creating extensions that connect each panel, whatever its position, with the joint in the joint plane.

Instructions for implementing this technique are given below and include step-by-step examples using the rigidly foldable M3V twist mechanism. A summary of the steps is represented in Figure 3.3.
Figure 3.3: There are 7 steps to design a thick origami model that preserves the kinematics and allows full range of motion using the offset panel technique

Step 1. Model Selection. Select an origami source model that gives the desired motion and/or form. The source model must be rigid/flat-foldable. When panels are constrained to be planar, the source model must also be sortable.

Example: We chose the M3V twist shown in Figure 3.1.

Step 2. Place Joint Plane. Choose the location of the joint plane, the plane within which all of the joints will lie. Although it is not a requirement, the design is often simplified by assigning the joint plane to be parallel to the panels or even coplanar with the face of one of the panels.

Example: We chose the joint plane to be the center of the closed panels (see Figure 3.4a). This minimizes the offset distances, which will reduce the potential for self-intersection during the folding motion.

Step 3. Index Panels. Assign each panel an index according to its position relative to the joint plane in the closed state. The joint plane is designated as “0”, the panel directly above it as “+1”, below it as “-1” and so on.

Example: Figure 3.4b shows the joint plane in the center of the indexed layers.

Step 4. Thicken Panels. Assign thickness to each panel based on the application.

Example: We assigned a uniform thickness of 3 mm.

Step 5. Offset Panels. Arrange the panels into the closed state according to the indices assigned in step 3. They can be stacked panel to panel or spaced with gaps between panels.

Example: Figure 3.5a shows the thickened panels stacked in indexed layers.

Step 6. Determine Joints. Extend each joint from the offset position of each panel to the joint plane using rigid extensions so that the axis of rotation lies in the joint plane even if both
Figure 3.4: An illustration of (a) Step 2 - Place Joint Plane and (b) Step 3 - Index Panels. Side views are shown to indicate index sequence. Solid lines represent panels and the dashed line represents the joint plane in the side view.

panels are offset from it [2]. This ensures that the rotational axes remain unchanged from those of the zero-thickness model throughout the folding motion.

Example: Figure 3.5b illustrates the joint alignment on the crease pattern and sample joint extension configurations. The extensions are rigidly attached to panels with length equal to the panel offset such that the rotational axis remains in the joint plane even if one or both panels are offset.

Step 7. Address Self-Intersection. To prevent panel-joint interference, create clearance holes in panels that lie between another panel’s joint and the joint plane. These holes guarantee that the mechanism can be assembled in the fully closed position. These clearance holes are necessary, but not sufficient to guarantee that the mechanism is able to move throughout the entirety of its range of motion. To guarantee full range of motion with no self-intersection, the entire mechanism
Figure 3.5: (a) An illustration of Steps 4 - Thicken Panels and Step 5 - Offset Panels. Rectangles represent thickened panels. (b) Step 6 - Determine Joints is shown. The side views show isolated individual joints and their adjacent panels.

volume needs to be mapped through the full motion, removing any intersecting material from one or both interfering surfaces. In many cases the clearance holes in the fully closed configuration will be sufficient to avoid self-intersection through the full range of motion.

Example: Clearance holes are located by drawing clearance boundaries around joints and reflecting them about fold lines to their positions on the interfering panels as shown by shaded areas in Figure 3.6.
3.4 General Examples

We present several configurations of the offset panel technique that are kinematically equivalent to the zero-thickness structure. The following configurations are not an exhaustive list, but they illustrate some of the capabilities and limitations of the offset panel technique.

The models were created using 3 mm acrylic sheet stock and approximated joints using adhesive fabric tape to create hinges with minimal play. Each configuration is a version that is kinematically equivalent to the zero-thickness approximation paper model shown in Figure 3.1.

3.4.1 Uniform Thickness Panels

The simplest configuration demonstrates uniform panel thickness. Figure 3.7 shows the M3V twist of Figure 3.1 in 3 mm thick panels. By placing the joint plane at the center of the model and offsetting panels to either side, the sum of the distances from panels to the joint plane is minimized, which, in turn, minimizes the number and size of the required clearance holes. Each panel offset is determined by the sum of thicknesses of the panels that lie between that panel and the joint plane.
Figure 3.7: Uniform thickness model shows the M3V twist in (a) open, (b) midway, and (c) closed positions. (d) A side view with the joint plane at the dashed line.

### 3.4.2 Offset Joint Plane

It may be desirable to have relatively large distances between panels in the open state. This can be achieved by offsetting all of the panels to one side of the joint plane. The location of the joint plane will affect the positioning of the panels as well as the volume swept by panels in motion. The joint plane is not restricted to a panel’s face. Figure 3.8 shows a model with all panels on one side of the joint plane. Each panel offset is equal to the sum of thicknesses of the panels between that panel and the joint plane plus the offset distance.

### 3.4.3 Gaps Between Panels

The previous models had no spacing between panels in the closed state. However, gaps between panels could be beneficial, for example, in a folded wiring board to provide clearance for surface-mounted devices that extend above/below the panels. By offsetting the panels such that spaces exist between them, a model with gaps is created (Figure 3.9). The offset distances are now determined by the same sum of panel thicknesses plus the sum of the gaps between the panel and the joint plane.
Figure 3.8: Far offset model is made with all panels offset to one side of the joint plane in the closed position. This results in the panels spaced far apart in the open position and requires more clearance holes due to more interfering panels. (a) Open, (b) midway, and (c) closed positions shown. (d) A side view with the joint plane at the dashed line.

Figure 3.9: This model is designed with panels that are spaced apart in the closed position. This has similar open position as the fully compact model but with greater offset distances between panels. (a) Open, (b) midway, and (c) closed positions shown. (d) A side view with the joint plane at the dashed line.

3.4.4 Arbitrary Uniform Thickness Panels

The offset panel technique accommodates any thickness. Figure 3.10 shows the same model as Figure 3.7 with panel thickness four times the previous model’s thickness. The farther the panels are offset from the joint plane due to joint plane location or thickness of interior pan-
Figure 3.10: This model is four times as thick as the initial thick model. The thickness accommodation capability is clearly shown by this very thick model. (a) Open, (b) midway, and (c) closed positions shown. (d) A side view with the joint plane at the dashed line.

Figure 3.11: This model is made from panels all with different thicknesses. (a) Open, (b) midway, and (c) closed positions shown. (d) A side view with the joint plane at the dashed line.

... the larger the volume that is swept by the panel and joint, which generally requires increased self-intersection clearance.

### 3.4.5 Variable Thickness Panels

Different panels can have different thicknesses, not all applications require that all mechanical system panels be equal thickness. Figure 3.11 shows the example model with panel thicknesses ranging from 3 mm to 12 mm.
3.4.6 Morphing Volumes

Panels do not have to be sheet-like. As long as the relative joint positions remain fixed within the model, any panel can take on any 3D shape, as long as intersections are avoided during deployment. This allows the creation of a structure with one unique shape when closed that morphs into a different shape when opened.

In Figure 3.12 we show one such example. We begin with a split-diagonal MVMV twist (adding a fold across the diagonal of the square twist to create a rigidly foldable structure), using the crease pattern shown in Figure 3.12a. We cut away the four corners of the crease pattern and erect eight cubes on distinct facets of the pattern and thicken the panels according to the offset panel technique. The result is a structure that, in the folded state, forms a larger cube, but in the unfolded state, takes on a dramatically different shape, with each cube rotating through a unique path throughout the folding motion.

3.5 Conclusions

Using the offset panel technique, one can design a deployable structure using finite-thickness panels while preserving the full range of motion of a zero-thickness idealized origami mechanism. The offset preserves the source model’s kinematics so long as the joint rotational axes are unchanged from the zero-thickness model. Preserving these joint relationships guarantees that the kinematics are equivalent, so the link/panel size and shape can change freely. However, self-intersections must be avoided to ensure the full range of motion, generally, by adding clearance holes. Suitable choice of the location of joint plane and the joints themselves can minimize the need for clearance holes and in some cases, eliminate them entirely.

Possible small scale applications include packaging, display stands/cases, foldable circuit boards, and solar panels. On a larger scale, the offset panel technique could prove beneficial in morphing architecture, deployable structures, temporary shelters, and deployable solar arrays.

A valuable area of future research would be the development of systematic methods for determining clearances required to avoid self-intersection.
Figure 3.12: This MVMV square twist crease pattern (a) was used to create the above morphing cube. The shaded regions show where the small cubes were added. (b) Open, (c) midway, and (d) closed configurations shown.
CHAPTER 4. ORICEPS: ORIGAMI-INSPIRED FORCEPS

This paper presents the conceptualization and modeling of a compliant forceps design, which we have called Oriceps, as an example of origami-inspired design that has application in a variety of settings including robotic surgeries. Current robotic forceps often use traditional mechanisms with parts that are difficult to clean, wear quickly, and are challenging to fabricate due to their complexity and small size. The Oriceps design is based on the spherical kinematic configurations of several action origami models, and can be fabricated by cutting and folding flat material. This design concept has potential implementation as surgical forceps because it would require fewer parts, be easier to sterilize, and be potentially suitable for both macro and micro scales. The folded and planar characteristics of this design could be amenable to application of smart materials resulting in smaller scale, greater tool flexibility, integrated actuation, and an adaptability to a variety of tool functions. The suitability of shape-memory materials for use in Oriceps is discussed.1

4.1 Introduction

The medical device industry is a rapidly evolving and highly competitive market. The introduction of surgical robotics into the industry has intensified these qualities and introduced a new set of unique challenges that need to be addressed. Specifically, there is a need for tools that can be scaled down, sterilized easily, and produced at lower costs.

The Origami-Inspired Surgical Forceps, or Oriceps, shows potential to reduce production costs while maintaining functional properties. Scalability is achieved through monolithic design and planar production processes. The scope of this project is the gripping function of forceps, and does not include the integration of Oriceps with an entire robotic system.

1 This chapter has been published in Smart Materials, Adaptive Structures, and Intelligent Systems Conference 2013 (SMASIS2013) entitled "Oriceps: Origami-Inspired Forceps" (SMASIS2013-3299) [29]. Co-authors include Landen A. Bowen, Clayton L. Grames, Spencer P. Magleby, Larry L. Howell, and Terri C. Bateman
4.2 Background

Over the past 50 years, origami has grown in its popularity and complexity. More recently, origami has been a trending topic in engineering design, making many common products foldable and collapsible [30]. Action origami, origami designed to move, has recently been classified into categories based on its spherical mechanism structure [9]. Many action origami models were considered in seeking inspiration for Oriceps, the majority of which were from books written by Robert Lang and Jeremy Shafer [5, 6, 8, 31].

Origami can be viewed as a compliant mechanism when folds are treated as joints and panels as links. Action origami shares many characteristics with lamina emergent mechanisms (LEMs), a type of compliant mechanism that is planar and monolithic with motion out of the plane of fabrication. LEMs, like origami, are not limited to single layer mechanisms. By using multiple layers, LEMs, again like origami, can achieve impressive motion [32]. When multiple layers are used they are referred to as multi-layer lamina emergent mechanisms (MLEMs). Many of the principles in LEMs/MLEMs design and fabrication apply to origami and were utilized in the design process of Oriceps.

The use of compliant mechanisms in minimally invasive surgery is becoming more common. Minimally invasive surgery requires small tools to minimize incisions and tissue damage. By replacing pin joints with compliant flexures, compliant mechanism design allows for smaller tools than traditional kinematic design would allow. Extensive research has been performed in adapting compliant mechanisms to improving minimally invasive operations [33–35].

The majority of consumer products are designed with customer needs in mind, known as a market pull design process. The Oriceps design however, followed a technology push process where a concept came before the need. The technology push process can be an effective tool in driving innovation and creativity [36].

Smart materials are materials which respond to specific stimuli in the environment around them. Smart materials have been shown to have many applications, one of which is actuation. Some examples of smart materials suitable for the actuation of compliant mechanisms (and origami) are shape memory alloys, dielectric elastomers, and piezoelectrics [37].

There has recently been considerable interest in creating self-folding origami using smart materials. Shape memory alloys have already been used to fold several origami designs from the
same sheet of material [38–40]. Work has also been done on a method for self-folding of origami designs by application of a voltage or magnetic field [41].

4.3 Oriceps

Oriceps is an alternative forceps design that is formed from a single planar sheet of material. The design of Oriceps originated from Shafer’s “Chomper” [6] shown in Fig. 4.1. The original dimensions came from the paper model and were modified to the dimensions shown in Fig. 4.2.

When folded, the clamping motion is achieved with a single input force to the center panel. Pushing or pulling from the back will cause Oriceps to close or open. This motion is demonstrated by the functional model shown in Fig. 4.3 and Fig. 4.4. Alternatively the center panel could be fixed, applying symmetric moments or forces to the side panels to achieve the desired clamping motion.

Achieving sufficient mechanical advantage without sacrificing functionality and size is a design challenge because by using a compliant mechanism, a considerable portion of the input energy is lost to member deflection.
Figure 4.2: Oriceps was designed with scalability in mind. The current dimensions of Oriceps are parametric, allowing for many different final sizes.

Figure 4.3: Functional prototype of Oriceps in its closed state, achieved with a simple push to the back panel.

4.4 Mechanism Selection

Potential models were evaluated according to how they would satisfy customer needs. As prototypes in paper are fast and relatively simple to make, many different models were reviewed during the early stages of development. The most promising designs were compared using a screening matrix.
Figure 4.4: Functional prototype of Oriceps in its open state, achieved with a simple pull to the back panel.

Table 4.1: Design objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical advantage</td>
<td>Competitive with a range of 0.1 - 0.35</td>
</tr>
<tr>
<td>Material suitability</td>
<td>Suitable for compliant applications</td>
</tr>
<tr>
<td></td>
<td>$S_t / E \times 1000 \geq 10$</td>
</tr>
<tr>
<td></td>
<td>Biocompatible</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Balance between compliance and stiffness</td>
</tr>
<tr>
<td></td>
<td>Limited deformation around gripped object</td>
</tr>
<tr>
<td>Scalability</td>
<td>Monolithic if possible</td>
</tr>
<tr>
<td></td>
<td>Planar production processes</td>
</tr>
</tbody>
</table>

### 4.4.1 Design Objectives

The four design objectives determined to be most important were: mechanical advantage, material suitability, product scalability, and mechanism stiffness. Many other important areas of functionality were identified such as force capabilities, range of motion, reliability/reusability, disposability, clamping angle, and cost/manufacturability. The most important items are summarized in Tab. 4.1.
4.4.2 Paper Prototyping

While investigating various action origami models for suitable motion, Shafer’s “Chomper” [6] was found to have general motion that was appropriate for forceps or similar vice-like tools. Also, its one-degree-of-freedom actuation may allow for simple actuation. Most action origami models are made of interconnected spherical mechanisms and the combinations can become complex. However, the “Chomper” is made up of only two coupled spherical 4R mechanisms, resulting in a relatively simple one-degree-of-freedom system.

With the “Chomper” as a base model, there was a need to find an origami variation that would be most suited for use as Oriceps. Many different models were designed, folded, and compared qualitatively for their ease of use, gripping area, and applicability. Those models which performed the best were then entered into a matrix and analyzed across several key categories.

Models that offered advantages over the “Chomper” in a particular category were scored with a plus (+), while models that exhibited inferior performances were scored with a minus (−). Any models that appeared to be even with the “Chomper” in a category were scored with an equal sign (=). The pluses and minuses were then tallied for a final score. The result of the evaluation matrix can be seen in Tab. 4.2.

Most of the variations scored lower than the original model. A variation with four spherical mechanisms rather than the two found in the original model tied with the original as the best-scored designs. The four-spherical-mechanism version was selected because it offered a greater surface area for gripping. The addition of two spherical mechanisms (for a total of four) replaced the beak-like gripping surface of the Chomper with two planar links that converge together, thus creating a larger gripping surface. The difference is clear when seen side by side as in Fig. 4.5.

4.5 Geometry

The Oriceps structure is made from four symmetric sets of four folds which results in bi-axis symmetry. This creates a mouth-like feature (shown in Fig. 4.6) that closes when the sides deflect relative to the center panel. This structure can be defined by the length of the side (S), length of the mouth (L), separation width (s), separation height (d), interior mouth angle (θ, symmetric for the other interior folds), input link angle (α), and mouth position angle (ϕ). The separation
Table 4.2: Design screening matrix

<table>
<thead>
<tr>
<th>Name</th>
<th>Flat foldable</th>
<th>Ease of use (DOF)</th>
<th>Manufacturability</th>
<th>Mechanical advantage</th>
<th>Ease of actuation</th>
<th>Gripping surface v. size of tool</th>
<th>Range of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Chomper</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>=</td>
<td>0</td>
</tr>
<tr>
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<tr>
<td>Elderly Venus Fly Trap</td>
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<td>-</td>
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<td>+</td>
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<td>-1</td>
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<tr>
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<td>+</td>
<td>+</td>
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<tr>
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<td>-</td>
<td>=</td>
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<tr>
<td>Back Chomper</td>
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<td>=</td>
<td>+</td>
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Figure 4.5: 2SM (left) and 4SM (right) models side-by-side.

height and width have no effect on the motion of the chomper, but do determine the gripping surface and distance between jaws. The parameter $\theta$ is bounded in this configuration by $45^\circ$ and $90^\circ$. As $\theta$ approaches $45^\circ$, $\phi$ converges to $90^\circ$ making the closed jaw separation equal $d$. When $\theta$ approaches $90^\circ$, the input angle goes to $180^\circ$, resulting in a flat sheet. As $\alpha$ approaches $180^\circ$,
The relationship between $\alpha$ and $\phi$ changes with the other parameters $S$, $L$, $D$, and $\theta$.

4.6 Materials

Multiple material types were evaluated according to the criteria listed in Tab. 4.1 for use as prototyping materials. The two best candidates according to these metrics were Delrin (Acetal) and Polycarbonate.

Initial prototypes demonstrated that the chosen materials were too stiff with uniform thickness even after decreasing flexure length at folds. When the material thickness was decreased, the links were too flexible, eliminating force transfer to the output. To address this problem, principles from multi-layer lamina emergent mechanisms (MLEMs) were considered.

Often MLEMs use different layers to perform unique functions, such as structure, actuation, and motion. This allows the design of each layer to be simple and optimized for its given purpose. This layering process was applicable to the Oriceps design.

By layering materials as in MLEMS, link rigidity was maintained while increasing flexibility. This led to the consideration of a relatively new flexure material, metallic glass. Metallic glass has a very high yield strength to modulus ratio, allowing for controlled motion without plastic deformation. Several models with rigid links made from plastics overlaid on a metallic glass base, shown in Fig. 4.7, were made and demonstrated desirable properties.
4.7 Prototypes

The majority of the prototypes were created with a laser-cutter. This type of planar manufacturing is inexpensive and easy to implement. The laser-cutter was versatile in cutting paper, plastic, and the metallic glass. Oriceps are unique in that they can not only be produced out of sheet goods, but they can also be transported flat (Fig. 4.8) and folded up for use.

Using planar manufacturing processes and the parametric Oriceps design discussed earlier allows for easy scalability. The preliminary prototypes shown in Fig. 4.9 were created in three sizes: 2, 1, and 0.75 inch diameter.

Prototyping of Oriceps proceeded through various stages of complexity and materials. A combination of qualitative and quantitative methods were used to evaluate each prototype.

To allow for modular testing of different Oriceps designs and to demonstrate the feasibility of robotic actuation, several functional prototypes were created. These prototypes consisted of a clear polycarbonate tube to represent the tool housing, a stainless steel rod to act as the actuation input, and tabs added to Oriceps to act as fixtures to the tubing. The tabs were inserted into slits cut into the sides of the tubing and the model was actuated by pushing or pulling the center link with the steel rod. This configuration can be seen in Fig. 4.10. This set-up allowed for variations of Oriceps to be exchanged readily for testing of different designs.

Figure 4.7: Multi-layer Oriceps design with rigid links and metallic glass flexures.
Figure 4.8: This monolithic, planar Oriceps design was laser-cut. The planar nature of Oriceps allows for fast and easy manufacture.

Figure 4.9: The Oriceps design allows for scalability, as demonstrated by 2, 1, and 0.75 inch diameter prototypes.

4.8 Actuation Consideration

The simplicity of Oriceps design allows for alternative actuation methods. While the initial prototypes utilized a simple push rod actuator, using smart materials for actuation has much potential. Shape-memory materials are the most promising of the smart materials considered.

Shape-memory materials or SMMs include shape-memory alloys, ceramics, and polymers that will return to an undeflected, or a remembered state after being plastically deformed when acted upon by a stimulus, usually heat. Preliminary research shows promise that SMMs can repeatedly provide large displacements necessary to open and close the Oriceps. SMMs are not
known to transform quickly, however the smaller the material, the faster the transition [37, 42]. In particular, a two-way SMM could have both the open and closed states in memory, allowing for quick open and close motions.

4.9 Conclusions

4.9.1 Future Work

Oriceps has demonstrated potential but is still in the early stages of development. Improvements in the next generation design include minimizing unnecessary deflection in the model by modifying flexure geometry to optimize force transfer. Link shape can also be easily modified to provide desired gripping surface and function.

System integration will also be important. Oriceps must be able to not only grip an object, but have the flexibility to get in position to grip the sample.

Prototyping with SMMs and other smart materials will lead to design changes that will allow for novel actuation and a more integrated Oriceps design.

4.9.2 Alternative Applications

The Oriceps concept is applicable beyond surgical applications. Possible areas of use range from remote-controlled space tools to household items like salad tongs and even children’s toys.
There is potential that currently unconsidered smart materials could be applicable, leading to new ways in which the Oriceps design could be applied.

4.9.3 Conclusion

Oriceps’ monolithic origami design can be manufactured on many scales to accommodate a wide range of functions. The planar nature of the design allows for inexpensive manufacture. Compared to current robotic forceps, this design drastically reduces part count, cost to produce, and could be disposable. Oriceps has the potential to benefit from integration of smart materials, which would provide a self-contained actuation method.

4.10 Acknowledgment

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CHAPTER 5. CONCLUSION

5.1 Conclusions

The distinct, main contribution made by this thesis to the field of origami-inspired design is the newly developed offset panel technique for thickness accommodation. A second significant contribution is an origami-inspired device illustrating thick origami design in a practical application of medical forceps.

The offset panel technique addresses limitations seen by other thickness accommodation methods. This technique is currently the only method of accommodating thickness that both preserves the kinematics of an origami source model and enables full range of motion. The general nature of the offset panel technique allows many novel configurations to be realized that are not possible using other techniques.

The origami-inspired forceps (Oriceps) were designed by choosing an origami model with desired motion and adapting it to meet functional requirements. This process was in part motivation for the offset panel thickness accommodation method. The Oriceps show the process of developing mechanical systems through the utilization of kinematics identified in origami. The Oriceps also show some challenges with thick origami-inspired design that can be alleviated through applying thickness accommodation methods.

5.2 Future Work

I propose three future topics that would provide high value to the field of thick origami-inspired design.

- The first and foremost future work to be pursued should be applications designed using thickness accommodation methods. It is likely through developing applications that thickness accommodation methods can be more fully developed for complete benefit. Having
thick origami-inspired designs with well documented processes are crucial to making thickness accommodation methods viable options for designers.

- Second, the design process using the offset panel technique is time consuming with a tedious assembly method. A program developed to perform the offset panel design would greatly reduce the time intensive process as well as empower designers. The program could receive a crease pattern with necessary parameters and then output the 3D model or cut pattern. This would ensure proper implementation of the method and more extensive use.

- Third, further development of viable joints and surrogate folds with the offset panel technique is needed. The technique relies heavily on joint properties and the behavior of the rotational axes as required to preserve the spherical kinematic properties. The development of new joints and identifying existing joints that provide necessary conditions to be used in the offset panel technique will further its ease of use and could open doors to new processes such as monolithic planar manufacturing eliminating the need for assembly.
REFERENCES


APPENDIX A. SUPPLEMENTAL MATERIALS

AN OFFSET CONSTRUCTION TECHNIQUE FOR THICK RIGID FOLDABLE ORIGAMI

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ABSTRACT
A novel method for thick, rigidly foldable, origami-inspired design is introduced. Origami panels are mathematically assumed to be planar with zero thickness. To accommodate thick panels while maintaining the same motion as the paper model, hinge rotational axes should lie along the folds in a common zero-thickness plane. Using this new offset panel technique, arbitrary panel thickness can be used. The construction begins with a rigid-foldable model’s panels stacked in order in their closed or stowed position. A joint plane is chosen to represent a zero-thickness virtual plane and each panel is connected to the chosen plane with vertical segments. The joint plane is not limited to panel surfaces and can even lie far offset from the stacked panels. The extension segments from the stowed panels rigidly connect the panel to a joint with its rotational axis in the chosen joint plane. When using planar panels, the offset panel technique requires that the origami fold pattern be rigid foldable and sortable. The length of a vertical segment is determined by the distance between each stowed panel and the chosen joint plane. Multiple panel thicknesses can be accommodated within the same model. Clearance holes may be required to avoid self-intersection of joints or panels. This technique can yield compact stowed structures that preserve the origami source model’s kinematics with full range of motion. The technique is demonstrated using well-known origami patterns in various configurations.

Key to vertical segments (Side View)

(a,b) - panel a is shown stationary, panel b is shown in stowed (black) and deployed (grey) states

Figure 1 - Depending on the panel order and separation, the hinge placement varies. The side view shows possible placement options with panel/hinge relations. The solid lines show the stowed position while the dotted lines show the open position. The black dots indicate the rotational axis of the hinge. The left 6 orientations are special cases when the chosen joint plane is the top surface of panel 0 (bottom of panel 1). When the joint plane lies offset from both panels, the general cases apply (right 3 orientations where n and m are panel numbers).

Figure 2 - Square Twist (Mountain-Valley-Mountain-Valley w/ center refinement crease) constructed using the offset panel technique. a). Fully deployed flat position with 180 degree openness (note: panels do not lie in a plane; however, all hinges are on panel 0’s top surface plane). b). A mid-way stable position. c). Fully stowed initial flat position with 0 degree openness and with all hinges at the panel 0 top surface plane.

1This one-page abstract was accepted/presented in the 6th International Meeting on Origami in Science, Mathematics and Education (6OSME).