Using the Offset Panel Technique to Develop Innovative Origami-Based Applications

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Using the Offset Panel Technique to Develop Innovative Origami-Based Applications

Michael Robert Morgan

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

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Master of Science

Origami, the art of folding paper, was once only an art form. In recent years, it has collided with the world of engineering and is acting as a source of inspiration for solutions to various engineering problems. Paper, the typical material used in the art form, is thin and works well for origami, but is not often suitable for use in engineering. Researchers have developed a handful of methods for accommodating thick/rigid materials in origami design. Most of these preserve only the kinematics of the model or its range of motion. Not only does the offset panel technique (OPT) preserve both the kinematics and the range of motion, it also allows for flexibility in design. This work focuses on the further development of the OPT and its potential to be implemented in real-world applications. The OPT provides design flexibility by allowing for the use of various and multiple materials, the modification of panel geometry, and the utilization of any rigid-foldable origami pattern. These and other capabilities are demonstrated in several application examples.

Keywords: origami, thick origami, offset panel technique, origami applications
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CHAPTER 1. INTRODUCTION

1.1 Motivation

For centuries, origamists of all ages, skill levels, and nationalities have been transforming flat sheets of paper into countless shapes, patterns, and sculptures. In some ways, origami, the art of folding paper, is very simple — for example, all that is required is the paper to fold. This makes origami very accessible for any student, hobbyist, or artist. In other ways, though, the art form is very complex. Many people view the art as being limited to patterns found in origami books, but this is untrue — origami is as unlimited as oil on canvas. There exist infinite possibilities of patterns and sculptures, some very simple and others extremely complex. Recently, scientists and engineers identified this combination of simple fabrication methods and the capacity for complex sculptures and patterns as having much potential to solve problems. Furthermore, they discovered that an origami model’s behavior is highly predictable based on its fold pattern. Since the clash of origami and engineering, research has continued to expand both realms and has resulted in fascinatingly innovative solutions to engineering problems.

One barrier that has repeatedly emerged and has impeded the use of origami as a source of inspiration is the inability to freely use thick materials. For most engineering applications, paper is not an effective material. These applications require some property that cannot be achieved with paper, such as shape, rigidity, or strength. In general, with rigidity and/or strength comes some degree of thickness. One reason paper works so well in origami is its minuscule thickness. One may succeed in folding a thicker material, but to implement a complex fold pattern in a thick material by folding does not work well. The application of methods other than folding, however, allows origami fold patterns to be used in materials other than just paper.
Figure 1.1: An origami vertex and spherical mechanism. The point at which the folds meet is the center of the sphere along which any point on the mechanism moves. The metal structure and hinges show that the behavior is defined only by the rotational axes.

1.2 Background

1.2.1 Modeling Origami

As we begin to consider the use of thick/rigid materials in origami, it is important to consider the subset of origami called rigid-foldable origami. This is because in most origami patterns, one or more of the facets or panels are required to deflect, but if we use rigid materials, the facets will not be able to deflect sufficiently to complete the folding process. A significant amount of research has been performed in order to identify the rules of rigid-foldability [1, 2].

Another field of study of interest is that of three-dimensional kinematics, more specifically, spherical mechanisms. When panels are seen as links and folds as rotational axes it becomes clear that a rigid-foldable origami model is just a chain of spherical mechanisms. A spherical mechanism is one in which any given point on the mechanism is constrained to move along a hypothetical spherical surface whose center is the point at which all of that mechanism’s rotational axes intersect (see Figure 1.1). The behavior of any kinematic mechanism is defined only by the rotational axes, the shape of the panels has no effect [3, 4].

Using concepts described above and others, researchers have developed software both to analyze/visualize the behavior of a rigid-foldable fold pattern and to generate fold patterns based
on a desired structure [5, 6]. It is important to note that all of these models and concepts use the zero-thickness assumption. As its name implies, when this assumption is made, the material is taken to have no thickness. Since paper is so thin, the zero-thickness assumption is appropriate for its use in origami.

1.2.2 Thickness Accommodation Methods

Several methods have been developed to solve the problem of “thick origami”. These include the axis-shift method, the offset joint method, the membrane folds method, the tapered panels method, the offset crease technique, the spatial linkages method, and the offset panel technique. Each of these has its own set of capabilities and limitations which are briefly described below.

The axis-shift method [7] allows thick models to fold by moving the joint from the center (zero-thickness) plane to the edges of the material as seen in Figure 1.2(b). The joint is shifted to the bottom plane of the material for a mountain fold and to the top for a valley fold. This allows a full 180 degrees of motion, but since the joints are no longer coincident with the zero-thickness plane, the kinematics cannot be equal to that of the zero-thickness model.

The offset joint method [8] is similar to the axis-shift method in that the joints are shifted to the edges of the material. In fact the axis-shift method’s illustration in Figure 1.2(b) is identical for this method. In this method, though, the panels are not restricted to be coplanar or of uniform thickness. This allows, for example, material in exterior panels to be removed leaving gaps for interior panels to fit inside of the exterior panels. The result is a fully compact model in the folded state.

In the membrane folds method [9], panels are attached to one side of a flexible membrane as depicted in Figure 1.2(c). The panels are trimmed at valley fold edges to avoid self-intersection. Trimming is not necessary for mountain folds as the thick panels adjacent to the fold rotate away from each other. The amount of material trimmed determines how much of the range of motion is preserved. The gaps created by the trimmed material introduce additional degrees of freedom which can be undesirable.

The tapered panels method [7] as shown in Figure 1.2(d) preserves the kinematics by leaving the joints at the center (zero-thickness) plane. Material at each hinge is then removed to avoid self-intersection during rotation, this gives the panels the appearance of being tapered.
Figure 1.2: Illustrations of a simple tri-fold pattern employing the thickness accommodation methods. (a) The zero-thickness model. This is the mathematical model which is well approximated with paper. (b) The axis-shift method shifts the rotational axes from the zero-thickness to the edges of the panels. (c) The membrane folds method mounts thick panels to a flexible membrane. (d) The tapered panels method maintains the location of the axes by tapering the edges of the panels. (e) The offset crease technique replaces each crease with a rigid offset. (f) The offset panel technique offsets the panels away from the joint plane but adds extensions to preserve the kinematics.

In the offset crease technique [10], rigid panels are mounted onto both sides of a flexible membrane. Each crease of the original pattern is replaced by a rigid offset and two rotational axes. The rigid offset allows the adjacent panels to fold completely. This method is illustrated in Figure 1.2(e).

The spatial linkages method [11] uses spatial mechanisms such as the Bennett linkage to achieve motion at each vertex as shown in Figure 1.3. Though the kinematics are not identical
to the source model, the dihedral angles of the panels are equal to those of the source model. The range of motion is also preserved. One of the major limitations of this method is that only a selected set of fold angles are possible. For example, a degree-4 vertex requires that two opposite angles be 90 degrees.

Like the tapered panels method, the offset panel technique [12] leaves the joints on the zero-thickness plane. The panels are individually offset from that plane in such a way that they ‘sort’ themselves as they move into the folded state as demonstrated in Figure 1.2(f). This method is flexible and allows for things such as varying panel thicknesses, very thick panels, spacing between panels, far offset panels, morphing volumes, etc [13].

1.2.3 Design Process

In our technological world, there are two ways that a technology meets a need. First, market pull refers to the need calling for a technology to fulfill it. The second is technology push in which a new technology is developed and inspires new products. Technology push often results in unprecedented and breakthrough products.

As thick origami is not being developed to meet a specific need, it can be described as an area of technology push. Though still fairly new, the development of thick origami has many implications which could push cutting-edge products into the market. Origami especially has
potential in systems where mass, volume, and/or cost need to be minimized. For cases where origami-inspired solutions are considered, general design processes have been developed [14, 15].

1.3 Objective

The objective of this research has been to aid in the breaking down of the previously described barrier which has prevented engineers from being able to apply origami concepts to real-world solutions. This objective was to be met by:

- Expanding the understanding of the offset panel technique. The technique is new and a limited number of models have been developed using it. It is believed that the OPT has untapped potential which can be exploited in a wide range of applications.

- Comparing capabilities and limitations of existing thickness accommodation methods. Several methods currently exist and while each has advantages over others, none of them are comprehensive. It would be beneficial for those who wish to employ thick origami ideas to refer to a side-by-side comparison of existing methods.

- Identifying and developing innovative applications of thick-material origami. While the OPT has been said to hold potential for application, no examples have been shown. The demonstration of the utility of the OPT could serve to motivate other engineers to not only use the OPT, but to use origami as a source of inspiration.

- Articulating principles for implementing the OPT in a design. In order for the OPT to truly reach its potential, it must first reach the hands of designers and engineers beyond our research group. Instructional materials and examples demonstrating and giving instructions for the implementation of the OPT would allow others to more readily apply it to their own designs.

In the following chapters, the efforts to meet these objectives are described. First, in Chapter 2, is a self-contained journal publication describing some of the capabilities of the OPT as well as a comparison of the OPT to the other thickness accommodation methods. Second, in Chapter 3, several fold patterns are adapted for thick materials using the OPT. Chapter 4 consists of descriptions of examples and applications of the OPT, some of which also include self-contained reports.
The inclusion of these self-contained works has resulted in some redundancy, particularly in the chapters’ background sections. As a visual supplement to many of the models and examples shown in the chapters of this thesis is a list of videos, sorted by their corresponding chapters, in Appendix A. A playlist containing all of these videos can be found here — https://goo.gl/g8Wdtd.
CHAPTER 2. TOWARDS DEVELOPING PRODUCT APPLICATIONS OF THICK ORIGAMI USING THE OFFSET PANEL TECHNIQUE

2.1 Introduction

In recent years, origami’s potential for innovative solutions facilitated by its complex behaviors, yet simple fabrication methods has caught the attention of scientists and engineers. Some of the proposed applications of origami include deployable space applications [16–18], nanostructure fabrication [19], robotics [20], and medical equipment [14, 21]. While origami’s potential can be seen and even explored using traditional paper origami, most engineering applications would generally require materials with stiffness and strength. With increased stiffness and strength, however, comes some degree of thickness, and as thickness increases folding becomes less and less feasible.

Several formal methods have been developed for accommodating thickness in origami-based design. These include methods that shift rotational axes to edges of panels [7, 8], mount trimmed panels onto membranes [17], employ spatial mechanisms at vertices [11], taper the edges of the panels [7], and replace creases with a rigid link and two axes to allow folding of adjacent panels [10]. The method used in this paper, the offset panel technique (OPT) [12], preserves the kinematics of an origami model and allows a full range of motion. While the benefits of these two traits can come at the cost of self-intersection and some complexity, the technique does allow for a variety of shapes, materials, and movements to be employed in a thick model based on a given origami pattern.

Previously, a number of basic configuration-related capabilities of the OPT have been shown [13]. For example, the technique can provide designers with flexibility as it accommodates uniform and varying panel thickness, gaps between panels, and freedom in joint plane placement. In this paper, we move beyond demonstrating the basic capabilities of the OPT (to accommodate
thick panels) to demonstrate its potential to facilitate the development of innovative origami-based products that use non-paper materials, thick materials, and/or non-planar shapes.

2.2 Background

As preparation for extending the application of the OPT, we briefly review three areas that, combined, lead to an understanding of adapting origami models and motions for thick materials to realize new ways to create mechanical products.

2.2.1 Modeling Origami

To take advantage of origami’s potential for application, it is useful to have mathematical models of their motion and behaviors. Origami can be modeled as a web of coupled spherical mechanisms where each vertex is the center of a spherical mechanism, each panel is a link, and each fold is a joint [1, 2, 4, 22–25]. Spherical kinematic mechanisms belong to a subset of three-dimensional kinematics in which any point on the mechanism is constrained to be coincident with a spherical surface whose center is the point of intersection of all joints within the mechanism. The behavior of a spherical mechanism is defined by the location of the rotational axes. In other words, if a link’s shape or size changes, as long as the rotational axes have not been altered, the motion will be the same [26, 27].

2.2.2 Thickness Accommodation

Mathematical models have been developed which have been used to predict the behavior of a given fold pattern [6] and which can generate crease patterns based on a desired form [5, 24]. These mathematical models usually assume zero-thickness materials. Due to paper’s relatively thin nature, zero-thickness is a suitable approximation for traditional origami. However, this approximation breaks down for thicker origami materials [28].

Several techniques have been developed to accommodate thick materials. Each of the thickness accommodation techniques has its own set of strengths, weaknesses, and limitations. Figures 2.1 and 2.2 illustrate seven methods, including the OPT, and Table 2.1 lists the methods and com-
Figure 2.1: An illustration of the concepts of different thickness accommodation methods. All images, except (e), are from [12]. (a) The zero-thickness model describes the basic kinematic behavior of the model. (b) The axis-shift method [7] shifts each rotational axis to either the top or bottom of the thick material. While slightly different conceptually, the offset joint method [8] can be illustrated identically. (c) The membrane folds method [17] mounts thick-material facets to a flexible membrane. (d) The tapered panels method [7] trims material from the panel edges to maintain the kinematics. (e) The offset crease technique [2] is similar to the membrane folds method, but calls for rigid material in the gaps between panels. (f) The offset panel technique [12] offsets each panel from a selected joint plane and extends the rotational axes back to the joint plane.
Figure 2.2: The spatial linkages method [11] is a thickness accommodation method which uses spatial linkages at the vertices of the origami pattern to achieve its motion. A single origami vertex is shown that employs such a mechanism. This illustration is separate because the method cannot be portrayed in the same two-dimensional form as the other methods. The red dotted lines indicate the rotational axes. This method was shown to work with degree-4, degree-5, and degree-6 vertices.

Table 2.1: A COMPARISON OF THICKNESS ACCOMMODATION METHODS.

<table>
<thead>
<tr>
<th>Method</th>
<th>Kinematics Preserved</th>
<th>ROM Preserved</th>
<th>Single DOF</th>
<th>Unfolds Flat</th>
<th>Application Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axis-Shift [7]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, varied thickness, Limited to selected fold patterns</td>
</tr>
<tr>
<td>Offset Joint [8]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, varied thickness, Limited to selected fold patterns</td>
</tr>
<tr>
<td>Membrane Folds [17]</td>
<td>No</td>
<td>Yes, if gaps between panels &lt;= 2*thickness</td>
<td>No, gaps allow movement</td>
<td>Yes</td>
<td>Deployed system requires tension at edges to keep membranes stretched</td>
</tr>
<tr>
<td>Tapered Panels [7]</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Required tapering of panels limits possible geometry and materials Panels required to be trimmed to avoid self-interference at vertices</td>
</tr>
<tr>
<td>Offset Crease [2]</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Fold angles and panel thicknesses limited by the spatial mechanism</td>
</tr>
<tr>
<td>Spatial Linkages [11]</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Cutouts in panels may be required to avoid self-intersection</td>
</tr>
<tr>
<td>Offset Panel [12]</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>
pares them against four characteristics that will be important to discussing applications for the OPT. Following is a description of these characteristics.

*Kinematics Preserved* indicates if the kinematics of the base origami model (a zero-thickness model) is preserved with the method. While matching kinematics may not be important for some applications, in many it will be essential to achieve the single-DOF, the consistency, or the predictability of a motion identical to the origami model.

*ROM Preserved* indicates whether or not the range of motion, from fully folded to fully deployed, is preserved. Many methods do not allow for full range of motion due to clashes of panels/edges. In some applications full motion may not be required, but in many there is a need to move through the full 180°.

*Single DOF* indicates if the method will result in a single degree-of-freedom (DOF) system (assuming that the pattern itself has a single DOF). Many rigid-foldable origami models have one DOF. For many applications, especially those implementing a deployable application, a single DOF is attractive.

*Unfolds Flat* indicates whether or not the thick origami system resulting from the method will be flat in its fully unfolded shape. Flat is defined in this case as resulting in a system where the entire upper face of each panel lies in the same plane. Traditional paper origami unfolds flat by this definition. Most of the methods do not produce fully flat configurations as the panels are offset or tapered. The OPT does not result in flat configurations, but the offset panels (or panel substitutes) can be parallel to the joint plane.

*Application Considerations* presents notes on key aspects which should be considered when creating practical applications with the method. Depending on the application, the considerations may be impediments or used as advantages.

In this paper, the applications that are presented take advantage of the OPT’s capabilities to preserve kinematics, allow for full range of motion, and open with a single DOF. OPT-based systems generally do not fold flat and have a tiered appearance in the open position. This is used as an advantage in some of the following examples.
2.2.3 Offset Panel Technique

One of the major advantages of the OPT is that it maintains both the kinematic behavior and the full 180° of motion [12]. The former permits designers to take advantage of the mathematical models already developed while the latter allows for fully opened and closed models. The OPT also allows for flexibility in a design. Since an origami-inspired design is constrained by only the preservation of the location of the axes and self-intersection, attributes such as varied panel thickness, spacing between panels, and boundless joint plane placement are all possible with the OPT [13].

2.3 Fundamental Capabilities of the Offset Panel Technique

A major benefit of traditional origami is the simplicity that it offers — the desired model is a product of a single monolithic piece of paper which undergoes no process other than folding. While some of this simplicity is lost in “thick origami”, there are at least two fundamental capabilities possessed by origami models implemented by the OPT which are not exhibited by traditional origami. These are the variation of panel geometry and the material(s) used in a design. We refer to these as fundamental capabilities because others are either subsets of them or results of combining them.

2.3.1 Panel and Joint Materials

With the option of using non-paper materials, it becomes clear that virtually any solid material can be utilized in origami design. Designers of origami-inspired products now have the ability to accommodate materials that are, for example, transparent/opaque, conductive/insulative, lubricative/abrasive, adhesive, stiff, modifiable, expansive, electrically charged, absorbent, or reflective.

Additionally, not only can a model be made of virtually any solid material, since thick origami panels are fabricated individually in most cases, the individual panels of a model can be assigned different materials. For example, Figure 2.3 shows a kinetic sculpture based on an origami fold pattern. In the design of this model, a lightweight material was desired for the moving panels, while strength was needed in the supporting ground panel. A lightweight foam board was chosen.
Figure 2.3: The unfolding of an origami-based kinetic sculpture which employs the OPT. This was part of an exhibit in BYU’s Museum of Art.

Figure 2.4: In the kinetic sculpture, the grounded panel is made of MDF while all others are made of a foam board.
Figure 2.5: A schematic of the pattern used in the design of the kinetic sculpture. (a) The square twist crease pattern. (b) A side view of the stacked panels and joint plane (represented by the red line). (c) The panel stack with offsets.

to be used for the moving panels and MDF was used for the ground panel. The different sculpture materials can best be seen from the back, as shown in Figure 2.4.

This kinetic sculpture is based on the square twist fold pattern shown in Figure 2.5(a). Figure 2.5(b) illustrates the closed stack of panels (looking down at the sculpture from the top). In this design, the panels all have an equal thickness of one inch and, while interference has been accounted for, the panel profiles have not been altered. Figure 2.5(c) shows the same panel stack but includes the offsets which have the same color as the panels to which they are rigidly attached. The offsets are shown to demonstrate the preservation of the axes’ locations which in the closed configuration all lie on a single plane (referred to as the joint plane) indicated by the dotted red line.

The next example shows the possibility of a foldable circuit board which uses the OPT. This is shown in Figure 2.6. All but one panel is made from a PCB substrate, while the exception is made of a metal plate intended to act as the ground layer. While simpler crease patterns (i.e., a tesselated tri-fold pattern) could offer the similar stowed-to-deployed area ratios, this pattern facilitates connections between each panel and its neighbors and a single DOF.

A square twist pattern, as illustrated in Figure 2.7(a), was used as a base for this circuit board. The illustration in Figure 2.7(b) shows the stacked panels from the side and Figure 2.7(c) shows the same panel stack with the offsets.
Figure 2.6: A foldable printed circuit board with one panel constructed from metal.

Figure 2.7: A schematic of (a) the pattern used in the design of the foldable circuit board. (b) A side view of the panel stack and the joint plane. (c) The stacked panels with offsets. (b) and (c) are 2X scale.
2.3.2 Panel Geometry

Perhaps the most applicable and inspiring capability of thick origami (the OPT in particular) is the large amount of freedom a designer has to alter the geometry of the panels. Once it is determined that an origami-inspired design will employ the OPT, the only limitations are the preservation of the rotational axes and the prevention of self-intersection. Panel material can be added and/or removed to add structure, give form, achieve motion, etc. Combining this idea with that of using various materials, not only is it possible to alter the shape of a model’s panel material, but panels can be replaced entirely by mechanical parts, electrical parts, displays, wheels, optical devices, solar panels, molds, etc. As long as axes are not moved and self-intersection is avoided, the model will maintain the kinematic behavior and the range of motion of the source model.

To demonstrate the manipulation of panel geometry, a model of a folding sphere is shown in Figure 2.8. From the closed configuration of a basic OPT model with uniform thickness, material is added to each panel in such a way that the model takes on the shape of a sphere. This is done without affecting the rotational axes and with care taken to ensure no self-intersection.

A version of the square twist as shown in Figure 2.9(a) formed the origami base of this foldable sphere. Figures 2.9(b) and 2.9(c) show the panel stack alone and with the offsets, respectively, and Figure 2.9(d) shows the panel stack with offsets and the material added to form a sphere.

As another example of non-constant panel geometry, see the toolbox in Figure 2.10. This model explores the utility of adding and removing material by carving out material from the panels to form compartments for supplies and adding material to panels to form the walls of the box. The box’s opening motion is shown in Figure 2.11.

The same square twist pattern as used with the kinetic sculpture was used for the toolbox, but with a different crease assignment as shown in Figure 2.12(a). To facilitate the closing of the box, a small space was added between the panels [13]. This spacing is shown in Figure 2.12(b) and the same panel stack is shown in Figure 2.12(c), but with offsets.

2.4 Resultant Capabilities - Stiffness and Strength

Having discussed the use of various materials and geometry, it is now befitting to examine an example of a capability that is a result of simultaneously varying materials and geometry. We
Figure 2.8: A kinematic simulation model of how panel geometry can vary, in this case to form a sphere.

Figure 2.9: A schematic of the pattern used in the design of the foldable sphere. (a) The crease pattern. (b) The panel stack and joint plane. (c) The panel stack with offsets. (d) The panel stack with offsets and modified panel geometry.
Figure 2.10: An electrical engineer’s toolbox created from an origami crease pattern and the OPT in (a) the unfolded position and (b) the folded position.

Figure 2.11: A demonstration of the motion of the toolbox.
Figure 2.12: A schematic of the pattern used in the design of the toolbox. (a) The crease pattern. (b) The stacked panels and the joint plane (in red). (c) The stacked panels with added offsets.

Figure 2.13: This origami-based table supports a significant amount of weight. Unlike the other examples in this paper, the table is designed to unfold to an intermediate position that does not correspond to the zero-thickness model’s fully unfolded position.

will explore the use of materials commonly used in engineering combined with the necessary geometry to develop designs which can support loads and apply forces. Based on the design specifications of an origami-inspired product, a fold pattern can be selected which would give the desired behavior — a particular motion, mechanical advantage, shape, or unfolded/folded size ratio. After the desired pattern has been determined, materials with sufficient stiffness and strength to perform the desired task can be selected as well as any geometrical modifications necessary.
For example, an origami-inspired table is shown in Figure 2.13. In the folded configuration, the table is compact. In the unfolded configuration, the table is much larger and, based on the kinematics and the materials of the model, can support a significant amount of weight. The table’s unfolding motion is demonstrated in Figure 2.14. The table uses the same square twist pattern as the kinetic sculpture and also has the same panel stacking configuration (see Figure 2.5).

In the next example, we consider a lift. By using a single reverse fold, a substantial mechanical advantage is possible. In this case, the mechanical advantage is approximately 20 at the open state (top-left in Figure 2.15) and gradually decreases to 5 at its highest point (top-right in Figure 2.15). To withstand the stresses that accompany the loads and large mechanical advantage of this example, MDF was the selected material.

The lift employs a reverse fold which is a single vertex origami pattern as shown in Figure 2.16(a). Figure 2.16(b) shows the stack of the panels and Figure 2.16(c) shows that same stack with the offsets and altered geometry. To create the offsets for this model, the entire inner faces of
Figure 2.15: The origami-inspired lift mechanism shown through its motion as it lifts the black weight.

Figure 2.16: The schematic of the reverse fold pattern used in the design of the lift. The dotted red line represents the joint plane. (a) The fold pattern. (b) A side view of the panel stack. (c) The panel stack with offsets which in this case are large and cover the majority of the inside face of each green panel.
the long green panels were extended inward to the joint plane while leaving clearance for the small blue panels.

### 2.5 Conclusion

Origami’s simple fabrication methods, infinite possibilities, and predictability provide it potential to emerge as a source of inspiration for many innovative designs. While paper origami models are useful for quickly visualizing and prototyping origami-inspired products, paper is often insufficient as a material for a finished product. However, the use of other materials in such origami-inspired designs often presents a handful of major difficulties including the folding of these materials and the interference issues that accompany it.

Several methods for accommodating thickness have been developed, each with its own capabilities and limitations. While the examples in this paper use the offset panel technique, the capabilities of accommodation of various materials, manipulation of panel geometry, and strength and stiffness can be applied to other thickness accommodation methods. These ideas add new and exciting possibilities for origami-inspired design and facilitate the development of creative solutions to real-world problems.
CHAPTER 3. DEMONSTRATING USE OF THE OFFSET PANEL TECHNIQUE TO REALIZE ORIGAMI PATTERNS WITH THICK MATERIALS

3.1 Introduction

Origami’s simplicity, deployability, predictability, and creative flexibility are traits that have attracted much attention from the world of engineering. Much progress has recently been made towards the challenge of exploiting these traits in the thick and rigid materials required by most real-world applications. One thickness accommodation method that has been developed is the offset panel technique (OPT) which preserves both the full range of motion and the kinematics of an origami model [12].

Previous work with the OPT has included a variety of designs based on different versions of the square twist pattern [29]. Some of these patterns are shown in Figure 3.1 and their applications can be seen throughout this thesis. To list a few of these applications, the pattern in Figure 3.1(a) was used with the morphing toolbox and the reduced panels model, Figure 3.1(b) was the inspiration for the kinetic sculpture and the folding table, Figure 3.1(c) was applied to the origami watch box and the folding sphere, and the pattern in Figure 3.1(d) was used in the creation of the circuit board. A review of these and other creative applications that have stemmed from virtually a single crease pattern has energized the exploration of other rigid-foldable patterns and their potential applications in thick materials.

3.1.1 Background

Rigid-foldability refers to an origami pattern’s ability to be folded without deflection of the panels [1, 24]. In such a pattern, all of the deflection occurs at the folds. This characteristic is of interest because in order to apply rigid materials to an origami pattern, the pattern must be rigid-foldable.
A rigid origami pattern can be seen as an interconnection of origami vertices and the folds which connect them. Each vertex can be modeled as a spherical mechanism which is defined as a kinematic mechanism in which any given point on it is constrained to move along a spherical surface whose center is at the intersection of all axes in the mechanism. When viewed this way, the origami panels are seen as kinematic links, the folds as rotational axes, and the vertices as the centers of the spherical mechanisms [4,22,23].
In kinematics there is a rule which states that a mechanism’s motion is defined solely by the rotational axes and, therefore, the shapes of the links have no effect on the behavior of the system [26, 27]. The OPT [12] is based on this concept. In the OPT, the panels are offset from a pattern’s zero-thickness model and extensions are added which extend from each fold edge of each panel back to the corresponding axis of the zero-thickness model.

The OPT has been shown to have potential for engineering applications. In a single origami model, it can allow for equally thick panels of arbitrary thickness, varied thickness among panels, arbitrary placement of the joint plane, gaps between panels, and more [13]. It has also been shown in various application examples, including a large kinetic sculpture, a foldable circuit board, a morphing box, and a table [29].

3.2 Patterns

The following are rigid-foldable patterns which have been adapted for thick materials using the OPT. These patterns were chosen because each is substantially different in its extreme positions (i.e., flat to tube-like and flat to diamond-shaped) as well as in its motion (i.e., flower-like opening motion and curling motion). This implies that each could lend itself to distinct and specific applications.

3.2.1 Hexagonal Twist

Based on work done with origami twists [1], this hexagonal twist has a flower-like opening motion. The crease pattern and panel stack schematic is shown in Figure 3.2 and the prototype in Figure 3.3. The design of this OPT model was quite simple. This is partially due to the fact that with the joint plane placed in the middle of the stack, the length of the longest offset is equal to only one material thickness. Additionally, this model required no clearance holes in the panels. This will always be the case when the joint plane is placed in the middle of a model with a stack of four or fewer panels.
Figure 3.2: An illustration of the crease pattern and panel stack for a hexagonal twist. In (a) is shown the crease pattern (the colored panels are the same panels shown in (b) and (c)), (b) a side view of the panel stack, and (c) the panel stack with offsets. The red lines represent the chosen location of the joint plane.

Figure 3.3: An OPT hexagonal twist in (a) the closed position and (b) the open position.

3.2.2 Degree-5 Hexagonal Pattern

This pattern, which has been used to make packaging boxes, is very similar to the previous pattern. The main kinematic distinction is that rather than degree-4 vertices, this pattern has degree-5 vertices which allow for different motion and add degrees of freedom. This was implemented by adding a crease that splits the kite-shaped panels as shown in Figure 3.4. The physical model is shown in Figure 3.5. Since this pattern is not flat-foldable, the panel stack schematic is not shown. This degree-5 hexagonal pattern was also shown to work with the spatial linkage method [11].
Figure 3.4: A schematic of the degree-5 hexagonal pattern. (a) The crease pattern. (b) A side view of the open pattern and joint plane. Since the pattern is not flat foldable, a panel stack cannot be shown.

Figure 3.5: An OPT hexagonal pattern previously used to make boxes in (a) the closed position and (b) the open position.

3.2.3 Bird Base

Next, the traditional bird base crease pattern is examined. In Figure 3.6, the fold pattern is shown along with the panel stack without and with offsets and in Figure 3.7, the physical model is shown in the open and closed positions. A thick model of this pattern was previously created using the offset crease technique [10].

We will first examine half of the bird base pattern (the colored half in Figure 3.6). The symmetry in the pattern allows us to design the halves separately, fabricate them separately, and hinge the halves at the symmetry line. The reasons for being able to do this are described in detail.
Figure 3.6: An illustration of the crease pattern and panel stack for half of a bird base. In (a) is shown the crease pattern, (b) the panel stack, (c) the panel stack with offsets, and (d) the mirrored pattern. The red lines represent the chosen location of joint plane.

Figure 3.7: An OPT bird base in (a) the closed position and (b) the open position.

in the next section. Doing this means that there are now two joint planes (as shown in Figure 3.6(d)) and that while the kinematics of each half is equivalent to the zero-thickness model, the kinematics of the entire model are not. The model in Figure 3.7 was built to demonstrate this idea of symmetry, but the same bird base pattern could be designed using the OPT to have a single joint plane and equivalent kinematics.

Again in this half-pattern, the panel stack is four layers thick which means that it was not necessary to create voids to account for self-intersection. In the open configuration, this results in an unbroken solid square as demonstrated in Figure 3.7(b).
Figure 3.8: An illustration of the crease pattern and panel stack for an extended Yoshimura pattern. In (a) is shown the crease pattern, (b) the panel stack, (c) the panel stack with offsets, and (d) the mirrored pattern. The red lines represent the chosen location of joint plane.

Figure 3.9: An OPT Yoshimura pattern in (a) the closed position and (b) the open position.

3.2.4 Yoshimura

This extended form of the Yoshimura pattern [30], which is illustrated in Figure 3.8, has a unique folding motion. As it is folded from the open position, it curls up and the ends interweave until it forms a tube-like shape in the closed position. The open and closed positions are shown in Figure 3.9. This pattern is another example of using a pattern’s symmetry to simplify the design.
Figure 3.10: Three panels from an origami pattern demonstrating the need for clearance holes. (a) The panels without clearance and the offset and (b) the panels with the offset and clearance.

of a thick model. Unlike in the bird base pattern the edges of the panels at the line of symmetry (shown in green in Figure 3.8) do not remain coplanar. This can be fixed by adding offsets to panels which are not on the symmetry plane. The fix is exemplified in Figure 3.8(d) where offsets were appended to the blue panels.

3.3 Discovered Capabilities

3.3.1 Uninterrupted Profiles

Many models shown in this thesis have required voids in order to avoid interference between a panel’s offsets and the panels beneath it (between it and the joint plane). This comes as a result of a panel or panels which lie between a fold and the joint plane and is illustrated in Figure 3.10(a). In this figure, three panels of an origami pattern are shown. The green plane indicates the joint plane and the orange line represents the required location of the axis joining panels 2 and 3. Since panel 1 lies between the orange line and the axis edges (the vertical faces where the axis lies in the zero-thickness model, marked in blue) of panels 2 and 3, clearance is required to avoid intersection between panel 1 and the offset of panel 3. The clearance hole and the offset can be seen in Figure 3.10(b).

It may be desirable in many applications, however, for the model to have a solid uninterrupted profile. One simple way this can always be accomplished is by employing a pattern with
Figure 3.11: A schematic of a 4-thickness model which could result in an uninterrupted profile. This schematic is not based on a specific origami pattern. In (a) is shown the panel stack only and in (b) some of the offsets are added. The black circles represent the preserved locations of the axes.

A four-thickness stack. Many rigid-foldable patterns have panel stacks of four panels. Examples can be seen in Figures 3.2(b), 3.6(b), and 3.8(b). Patterns such as these have a special quality — when the joint plane splits the stack (there are two panel thicknesses on either side), they will never require clearance holes to avoid the aforementioned interference issues. This can be proven by considering three possible offset configurations in such a pattern.

First, we consider an axis shared by two panels each with a surface coincident to the joint plane (refer to the blue and green panels and the axis represented by the yellow circle in Figure 3.11). This axis is already on the joint plane, therefore offsets are not required.

Second, we look at two panels on either side of the joint plane. Any panel pair of this case in a model based on a feasible origami pattern and with unaltered geometry will not be in danger of interference with inner panels when offsets are in place. The red and orange panel pair and the green and orange panel pair in Figure 3.11 are examples of this case.

Lastly, we consider two panels on the same side of the joint plane that share a rotational axis such as the red and green panels depicted in Figure 3.11. One of these panels must be coincident with the joint plane and consequently will not require offsets. Panel pairs of this case will always have coplanar vertical faces at the shared axis (this plane is represented by the purple line in Figure 3.11(a)). Since these faces are coplanar, the offset would be appended to the end of the upper panel (red) as shown in Figure 3.11(b), and therefore cannot interfere with the lower panel in the pair (green). Since in four-thickness models there are no other panels between the red panel and the joint plane (besides the green panel which has already been discussed), interference will not be an issue.
3.3.2 Symmetry

In the patterns shown in this chapter, we see two examples of symmetric patterns. In one case, the panel edges at the line of symmetry remain coplanar throughout the motion, while in the second case they do not. Both cases will be discussed.

For the first case in which the panel edges at the line of symmetry remain coplanar, the bird base pattern will serve as an example. There are three things which allow for the division and simplification of the model - (1) the pattern has a line of symmetry, (2) each symmetric half is individually rigid-foldable, and (3) the symmetry line remains coplanar throughout the motion. Because of these traits, only half of the model needs to be designed, two separate halves built, and a hinge placed at the edge of symmetry. As previously mentioned, this means that each half has its own zero-thickness model and the kinematics of the joined model are not equal to the corresponding zero-thickness model.

Next, the Yoshimura pattern will be the example for the second case in which the panel edges at the pattern’s symmetry line do not remain coplanar. This can be seen in Figures 3.8(a) and 3.8(b) as the blue panels, though clearly on the symmetry line in the fold pattern, are not on the green line when folded. As shown in Figure 3.8(d), blue extensions were added to bring the blue panels back up to the line of symmetry. This works for the Yoshimura pattern only because the dihedral angles of the blue panels are equal to those of the red panels throughout the motion. The equal angles guarantee that the symmetry edges (including the those on the new offsets) remain coplanar.

In both of these cases, the models are able to be simplified greatly by decreasing the length and number of offsets required. This significantly reduces the part count as well as the complexity of the design. It is also important to mention that in order to take advantage of these simplification techniques, the line of symmetry must be a fold line or straight set of fold lines.

3.3.3 Simplified Tessellations

The Yoshimura pattern presents an interesting case in which the pattern results in a four-thickness model and not only has symmetry, but is tessellatable. This implies that any number of the repeated unit can be individually fabricated and joined together, resulting in a potentially
massive single-DOF thick origami system. This concept has potential to be incorporated into other
tessellatable patterns as well.

3.4 Conclusion

After observing so many potential applications emerge from a combination of the OPT and
the square twist pattern, an exploration of additional origami patterns was compelling. Four addi-
tional patterns were adapted for thick materials using the OPT, each with characteristics showing
potential for distinct applications. During the process of designing these mechanisms, new capa-
bilities of the OPT were discovered, namely, the exploitation of symmetry in an origami pattern
including the addition of offsets to a symmetry plane and an understanding of how clearance holes
in panels are not necessary for models with stacks of four or fewer panels.
As stated in the objectives of this thesis, it was desirable to demonstrate the potential held by the OPT to be implemented in real-world solutions. In an effort to exhibit this potential, this chapter is dedicated to showing and describing conceptual and applied designs which use the OPT.

4.1 Morphing Box

4.1.1 Background

In recent years, origami has become an area of high interest to scientists and engineers. In general, it is not the actual folding of paper that has caught the attention of engineers, rather it is the potential for innovative solutions presented by the complex behaviors yet simple fabrication that are characteristic of the art. While origami’s potential can be seen and even explored with traditional paper origami, paper is not a useful material for most engineering applications which require stiffness and strength. With stiffness and strength, however, comes some degree of thickness. Once thickness is introduced, folding becomes less and less feasible. A handful of formal methods have been developed for accommodating thickness in origami-based design, including the offset panel technique (OPT), which was developed within my own laboratory. This method is useful because it both preserves the kinematics of the origami mechanism and allows a full range of motion. Packaging has been identified as an area that could benefit from and take advantage of origami’s blend of simple fabrication and complex behavior characteristics. Also, since it would be desirable in most packaging applications to have a full 180° range of motion (fold compactly and unfold completely), the OPT was recognized as a promising approach to develop such an application. It became my goal to create a morphing origami-derived packaging application that:

- employs the OPT,

- has a single degree of freedom (DOF) for simple use,
Figure 4.1: An illustration of the MMVV square twist crease pattern.

- possesses common origami and packaging elements in order to simplify the design as well as the manufacturing,
- has a deployment ratio of at least 4 to achieve a substantially compact closed state,
- and exhibits an aesthetic and interesting motion.

A toolbox was chosen as the packaging application to be developed because it has a need to store many small tools and objects in an initially small volume. Additionally, as compared to disposable packaging, for example, such a consumer-oriented application would merit the manufacturing methods by an OPT model. Lastly, such a mechanism was seen as something that would be of interest to those who own and use toolboxes.

### 4.1.2 Functional Description

This origami-inspired toolbox employs the offset panel technique and the origami square twist fold pattern (see Figure 4.1) to create a morphing, deployable toolbox. It includes nine panels (corresponding to the square twist pattern’s facets) which incorporate compartments for small tools or hardware, pliers, screwdrivers, and other tools. Built on to three of those panels are four walls
which form the box when the mechanism is closed. Because of the motion of the model, it was also necessary to include snapping lids on four of the origami panels (not pictured here). All of the panels were 3D printed and snapped together at the hinges.

The toolbox is to be stored in the closed configuration. In this configuration, the panels are not accessible as they are ‘folded’ compactly. From this state, it can be easily deployed to the open configuration where all panels are accessible. In the closed position, its volume is 257 cubic inches while in the open configuration it envelops a volume of 1028 cubic inches, four times that of the closed state. This can be seen in Figure 4.2.

Perhaps the most attention-grabbing feature of this design is not necessarily its morphing, rather the alluring twisting motion it goes through in its deployment. This is demonstrated in Figure 4.3.

4.1.3 Design Process and Analysis

Rigid origami can be modeled as a system of coupled spherical mechanisms where each vertex is the center of a spherical mechanism, each panel is a link, and each fold is a joint [3]. Spherical kinematic mechanisms belong to a subset of three-dimensional kinematics in which any point on the mechanism is constrained to be coincident with a spherical surface whose center is the
Figure 4.3: An illustration of the single DOF opening motion of the toolbox.

point of intersection of all axes within the mechanism. The behavior of a spherical mechanism is defined by the location of the rotational axes. In other words, if a link’s shape or size changes, as long as the rotational axes have not been altered, the motion will be the same [26, 27]. Using this model, the behavior of a given crease pattern can be accurately predicted by modeling it as a web of spherical mechanisms as shown in Figure 4.4.

The key concept in the OPT and thus the design of the toolbox 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
Figure 4.4: A demonstration of how origami may be modeled as coupled spherical mechanisms. In (a) is shown Shafer’s Chomper [31] with the main vertices and folds traced. In (b), the corresponding folds and vertices are shown on two circles, each representing a single spherical mechanism; in this case, the two are coupled by the facets on either side of crease represented by the dotted line. Figures from [27].

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 mechanism, aside from consideration of self-intersection, which was addressed separately. We accomplish this requirement by creating extensions that connect each panel, whatever its position, with its corresponding rotational axes in the joint plane.

The first step in creating the OPT portion of the toolbox was the selection of the fold pattern to be used as the base mechanism. The MMVV (mountain-mountain-valley-valley, describes the folds around the center square) square twist fold pattern was selected due to its deployment ratio of 4 and its unique motion in which most of its facets remain parallel to each other throughout its deployment. The crease pattern can be seen above in Figure 4.1 and the paper model’s unfolding motion in Figure 4.5. The next step was to “stack” the panels of the origami model. The paper model shown in Figure 4.5 was useful in this step.
Figure 4.5: A paper model of the MMVV square twist fold pattern is shown as it unfolds. Compare to Figure 4.3.

With the panels stacked, a joint plane was chosen to be parallel to the panels and near the center of the stacked panels. The panels were then indexed relative to the joint plane. Following that, the panels were each assigned a thickness. In this design, each panel was given the same thickness of 0.5 inches. Once the panels were ordered and thickened, they were offset from the joint plane in such a way that they would stack face to face in the folded position. From here, offsets and joints were put in place at each crease of the crease pattern, the rotational axes all lying
on the joint plane. It was then necessary to take into account self-intersection that was introduced during the last step and clearance was added. This can be seen in the center square panel of the mechanism. While only two of the cutouts were necessary, the other two were included to give a more symmetric appearance.

Once the OPT model was complete, the toolbox features needed to be added. It was noted from the paper model that each of the four edges of the paper remained on a single plane throughout the motion. It was also observed that several of the panels were offset the same distance and orientation relative to the joint plane in both the open and closed states. These two things allowed for the walls of the box to be added to the edges of these panels. Next, with the thickened panels designed, there was plenty of volume to work with - desired profiles were identified and material removed from each panel to create the compartments.

This design demonstrates the potential usefulness of thick origami in engineering new systems. Applications include packaging, medical kits, jewelry boxes, hardware containers, and electronics. This design was 3D printed and could easily be adapted for injection molding, but all kinds of materials and processes could be used to manufacture similar products.

4.1.4 Conclusion

Origami as a source of inspiration is becoming increasingly popular. If engineers and designers were limited to paper, however, this would likely not be true and origami would remain but an art. With methods being developed to adapt origami for various materials, products and processes based on the art continue to roll out. Using one of these methods, the OPT, and some creativity, we have designed a morphing toolbox with a single DOF whose compartments and walls are directly integrated into the thickened origami panels. The square twist fold pattern granted both a deployment ratio of 4 and the aesthetic motion we desired to incorporate into the toolbox. Using a combination of kinematics, art, and innovation we successfully created a viable product which links the art of origami with the science of origami.
4.2 Origami Watch Box

4.2.1 Introduction

Objective

The objective of the project was to develop a high-end watch box based on the offset panels thick origami design technique for TAG Heuer. The team’s focus was to incorporate origami design into the company’s watch box standards. This would bring attention to the use of origami in engineering as well as create a box that enhances the timepiece it encases.

Background

Origami-Based Design Process A significant amount of research has been done to identify a process for origami-inspired design. One such process [15] is summarized as follows:

- Define problem
- Identify origami solution
• Modify fold pattern

• Integrate

**Opportunity**  The unique appearance and motion of previous models based on the offset panel technique (OPT) called for an equally unique application. The OPT showed potential to be used in packaging and it was suggested by representatives of our customer that it be used to develop a watch box. The company provided a set of requirements for such a box.

**Offset Panel Technique**  Accommodating thick materials in origami-based design has been of particular interest to engineers due to the fact that most applications with potential to employ origami patterns also require materials with more thickness and rigidity than paper. Mathematical models have been developed to predict the behavior of any given rigid-foldable origami crease pattern [1, 2, 5, 6], but these all use the assumption of zero-thickness materials which, again, is not suitable for most engineering materials. However, several methods have been developed to accommodate thick materials [7–12]. One of these is called the offset panel technique (OPT).

The OPT is useful because it preserves both the range of motion and the kinematics of the original (zero-thickness) origami model. It is based on the kinematics rule which states that the behavior of a kinematic mechanism is defined only by the relative location of its rotational axes [3, 4]. This means that the shape of the link or panel has no effect on the mechanism’s motion. The OPT offsets each panel from the joint plane to accommodate the thick material. It does this while leaving the rotational axes unmoved by extending offsets from the offset panel to the axes’ original location (based on the zero-thickness model) at each fold line. Since this is only a change to the panel shape it does not change the motion. A simple example of how this is done is shown in Figure 4.7. For more on this, see [12, 13].

One of the benefits of the OPT is that, since the motion of a mechanism is defined only by the rotational axes, there is a great deal of flexibility in the geometry of the panels. With this in mind, the panel shapes can be altered to approximate the desired shape - in this case, a watch box.
4.2.2 Process

Problem Definition and Requirements

The goal in this project was to create a watch box that reflected origami origins as well as meeting the stylistic and physical standards set by our customer. They expressed the desire for the watch to remain horizontal at all times and provided us with the following dimensions:

- Inner watch space of 8x8x3 centimeters
- Inner depth of lid of 2 centimeters
- Outer diameter of 9.5x18.5x18.5 centimeters
- Lid height of 3.52 centimeters and base height of 6 centimeters

These dimensions provided are the current dimensions of their boxes. They explained that the inner watch space dimensions should remain fixed but the outer dimensions could be altered as necessary.
The team also set some requirements of its own which were used as the criteria in the evaluation of the concepts discussed in the following sections. These requirements were:

- The box is stable in both opened and closed positions
- The box looks and feels like a watch box
- Opening the box is intuitive
- The motion of the box highlights the watch without distracting from it
- Watch fits inside when the box is closed
- The hinges must be able to withstand repeated movement

**Concept Generation for Origami Solution**

Two variations of the square twist fold pattern were selected as the base origami patterns and are shown in Figure 4.8. The intermediate step between the two patterns is shown Figure 4.8(b). In Figure 4.8(b), the grey area shows a single square twist pattern; this single square twist was reflected across and then the combination of the two was reflected downward. The lines that divide the large square into quarters are not fold lines, so they are removed in Figure 4.8(c).
Figure 4.9: On the left is shown the original shapes of the base and lid panels and on the right is their modified profiles.

Figure 4.10: An example of how thickness can be changed.

Not only did the team experiment with 2D origami fold patterns, but it sought to be creative with what had been learned about the OPT - that the shapes of the panels don’t matter to the behavior of the model. Some of the factors that were experimented with were:

- Panel geometry
  - Profile - Changing the 2D profile of a panel (the shape of a facet as seen in the fold pattern) is a great way to alter the look of a thick origami model. See both the base and lid panels in Figure 4.14(a). Their original profiles are in grey in Figure 4.9(a) and their altered shapes are greyed in Figure 4.9(b).
  - Thickness - Each panel can be assigned the same thickness or the thicknesses of each panel can vary wildly. See the base panel in Figure 4.14(b). Figure 4.10 shows the same model from the side. Figure 4.10(a) is before the modification and Figure 4.10(b) shows the model after the modification.
Figure 4.11: A simple 3D shape is given to one of the panels.

Figure 4.12: Panels are removed from the original model. The grey panels represent those eliminated.

- 3D shape - Not only can the thickness vary, but the panels need not be flat at all. Each can be given an arbitrary 3D shape. See the cutout in the base panel in Figure 4.14(a). The simple 3D shape is isolated in Figure 4.11.

- Moving panels - Panels do not have to be static rigid masses, they can integrate translating, spinning, flipping, and other moving elements. The final design implements such a feature in the product-lifting mechanism. See Figure 4.21F.

- Panel elimination - Panels can, in fact, be removed as long as the rotational axes remain in place. See Figure 4.14(b). In Figure 4.12, the eliminated panels are greyed.

- Location of joint plane - The location of the joint plane relative to the “stack” of panels has a great effect on the sweeping motion of the panels, as well as the open configuration. Figure 4.13 shows two examples of joint plane location. In Figure 4.14(c), the joint plane location matches that shown in Figure 4.13(b), where most of the others are represented by 4.13(a).
• Fold patterns - There exist many rigid-foldable fold patterns. As mentioned, the team chose to only explore a couple of them, but it is clear in the figures that the pattern makes a big difference. See Figure 4.14(d) vs. 4.14(e), where we used the different patterns in Figure 4.8.

The many concepts generated were narrowed down to the five candidate concepts which can be seen below in Figure 4.14.

In Figure 4.14(a) the joint plane is located between the second and third panels (when counting up from the bottom as “1”). In this model, the watch remains horizontal throughout the entire motion. It was decided, however, that the motion was not intuitive and it did not follow our customers stylistic standards. The moving panels appeared to be unnecessary and extraneous.

Figure 4.14(b) shows a box that is similar to that shown in Figure 4.14(a), but with some of the panels removed. This was done to minimize potential chaos in appearance and keeping the square twist design. The watch would sit in the bottom, enlarged panel, which would remain stationary while the rest of the box expanded and therefore remain horizontal. Eventually, this became one of the final two design concepts. This design was not selected as the final design because the team felt that the panels were distracting from the watch and did not keep with the style of our customer.

The box shown in Figure 4.14(c) is also a square twist model but the joint plane was moved. It was set between the first and second panels (when counting up from the bottom as “1”). This model has larger offset panels and the watch would be located in the center rotational panel. By having the watch located in the center it would be the main focus of the box, instead of the movement. The movement of the watch would increase the appeal of the origami aspect of the design, however, it went against the parameters given to us. The team decided that the large offset panels also did not meet our customers standards of appearance. For these two reasons this design was not selected as the final design.
Figure 4.14: The final five concepts generated in the concept generation stage.
The model in Figure 4.14(d) is based on a square twist pattern much like those in Figures 4.14(a) and 4.14(b). However, there are no slots in the center panel to make room for the offset panels. This would allow for a solid panel to place the watch on without any distracting slots. With this model, the team still faced the issue of a watch that does not remain horizontal. It was also found that there were some areas where the panels self-interfered. These things led to the elimination of this concept.

The model in Figure 4.14(e) is a partial combination of four square twists put together (see Figure 4.14(e)). Although it is created from square twists, the way that this mechanism opens differs. The panels open up more like a flower than twisting to open as do the others. The watch would be set in the center panel where it would remain horizontal while the box opened up around it.

As the concepts were evaluated against the requirements, a new requirement emerged. The team felt that with such a dynamic and surprising watch box, it would be a mistake to leave the product in a stationary position. At least two of the concepts called for this and were ruled out.

The team elected to move ahead with the concept shown in Figure 4.14(e). The team agreed that this design met all of the requirements given us by the company by keeping the watch horizontal and maintaining specific dimensions. It also maintained the sophisticated style of our customer, showed off the origami aspect of the box, employed a simple pattern, enhanced the watch, and showed potential for easily creating motion for the product.

### 4.2.3 Modification of the Fold Pattern

In the design of this box, it was necessary to further modify the selected pattern (the grey area in Figure 4.8(c)) because of the many constraints imposed by both the design requirements and the dynamic motion of the folding and unfolding box. It quickly became clear that it was not practical to design for the open (or closed) position alone. Any changes in either position substantially affected the other. One can begin to see this by observing the open and closed pattern in Figure 4.15. Figure 4.16 shows the modified crease pattern and the shapes of the rigid panels. Following is a discussion of some of the main constraints and the changes they inspired in the pattern.
Figure 4.15: An illustration of the open (left) and closed (right) initial pattern. The dotted red lines indicate the fold lines.

Figure 4.16: An illustration of the open (left) and closed (right) modified pattern. Again, the dotted red lines indicate the fold lines. Even though panel shapes and fold lengths have changed, the relative locations of the axes are identical to that in the above pattern, thus the motions are identical. Also included in this model is the inner yellow square. This is the open space for the watch to fit into. The dimensions for this space were a constraint given by our customer.

Figure 4.17: The modified pattern from Figure 4.16 superimposed onto our design of the box.
Perhaps the most obvious difference between the patterns in Figures 4.15 and 4.16 is the difference in the side panels (green). In the modified pattern, the side panels were practically inverted while the rotational axes remained untouched - see Figure 4.18. This was to avoid aesthetic clunkiness in the design and also allow for simpler attachment to the box lid. This part of the modified version cannot be folded from paper. However, since we were dealing with thick origami, this modification was easily accommodated.

It has been researched and demonstrated that, with the OPT, the panel geometry can vary wildly [29]. Panel geometry is a broad topic and only a handful of examples have been shown. In the design of this box, the geometry of this panel was modified to include almost none of the space it originally occupied, moving most of the material to the other side of the joint axes of the panel, as shown in Figure 4.18. This has interesting implications and could help to account for interference in elegant ways.

One set of related constraints is the inner square dimensions, the shape of the box exterior, and the axes in the pattern. The team previously determined that the exterior box shape (from the top view) should be a square for aesthetic reasons. This set of constraints at first seemed impossible to solve because the inner square had to fit within the inner rectangle (grey). Scaling the pattern to accommodate this would not change the outer rectangle shape with aspect ratio of 2:1. (This can be seen in the prototype shown in Figure 4.26). It is the relative angles of the axes that define the motion and the pattern could therefore be shrunken or stretched to achieve the desired outer shape, as shown in Figure 4.19. Relative to the original pattern, only small stretches were needed to solve the above mentioned problem.

Another obvious change in the modified pattern is the truncation of the square panels (blue) in the pattern. This was necessary because they would otherwise interfere with the sides of the
Figure 4.19: Since the relative angles between the axes (the axes shown in red) in this pattern determine the motion, the pattern can be essentially stretched or shrunken out of or into the black dotted lines. The two examples serve to demonstrate this idea. In Example 1, the pattern has been stretched in the vertical direction and shrunken in the horizontal direction. In Example 2, the pattern has been shrunken in both directions. In neither example have the angles between the red axes changed.

Figure 4.20: The modified pattern with the interior box geometry superimposed (black lines).

Box lids in the open position. This can be more easily seen in Figure 4.20 where the black lines correspond to the geometry of the box interior. This can also be seen in Figure 4.17.

4.2.4 Integration and Final Design

Overview

After choosing the final concept for the box, the next task was to create a physical prototype of the box. The team created the box by building a base that came up to the joint plane (Figure 4.21A) and split the lid in two so it opened from two sides (Figure 4.21B). Each side of the lid is connected to the folding origami mechanism (Figure 4.21C) so the box unfolds as the two sides are pulled open. In the center of the box is a square hole that holds the watch and its cushion (Figure
Figure 4.21: Some of the main features of the final design.

4.21D). A platform was placed just below the hinges for support and to cover the interior structure (Figure 4.21E). Fixed to two of the moving panels is a strap which lifts the watch as the box opens (Figure 4.21F). Not only does the box unfold but the watch moves as well. The lifting mechanism will be discussed in depth below.

The materials used were high density fiber board (HDF), a black faux leather, and Tyvek. Originally, the team planned to use chipboard for the structure of the box but it was unavailable. HDF had the desired thickness for the box and was stiff enough to hold the required shape. Faux leather was used to cover the outside of the box because it followed the sleek style of our customer and gave the box a classic feel. The inside of the box is covered with a flocking fiber with a red color which was selected to contrast against the black exterior.

The original design called for a silky material to cover the interior of the box. However, the team was concerned that the fabric would not fit perfectly along the panels of the box. These two things lead to the decision to switch from fabric to flocking to cover the box interior. Flocking provided for a smooth covering and would look virtually seamless. It also eliminated the challenge
of having to assemble the box and the fabric at the same time. This also applies to the hinges. They were initially difficult to cover with fabric but flocking allowed all parts to be fully covered.

To assemble the box, the team first attached the board for the outside of the box to the faux leather. The inside of the box was then assembled and fixed to the base panel. Once the outer, inner and hinge subassemblies were complete, all of them were assembled simultaneously so that everything would fit together.

**Hinge Fabrication**

It became clear during the process of prototyping and iterating that the hinge assembly would be difficult to construct. This is largely due to the over-constrained nature of this type of mechanism. One of the main challenges was to cut out both the thick panel material and the hinge material, mount the panels onto the hinge material with reasonable tolerances, and then proceed to wrap the rest of the panels. Since alignment during this process was so important, the team sought a way to eliminate the need to manually align the panels and the hinge material.

Thanks to Dr. Robert Lang, it was discovered that the laser cutter does not cut through metal. With this information, the team began to experiment with adhering the panel material to a sheet of aluminum foil. As a note, we found that when cutting along the edge of the wood, the heat would burn through the thin foil. We eventually moved on to sandwich the foil with the panel material on one side and the hinge material on the other. The process we used is described briefly:

1. After making the sandwich panel, cut the panel shapes and an outer boundary.

2. Remove the excess material and peel off the exposed foil.

3. Cut the hinge material.

4. Perform any necessary assembly.

**Lifting Mechanism**

As mentioned, it was desirable to achieve some kind of motion for the watch. The team opted to harness the natural motion of the box to create a lifting motion. A strap was fashioned
Figure 4.22: A section view of the assembled box showing the lifting mechanism. The colored panels are the same as previous patterns, the black part is the strap used in the lifting mechanism, and the yellow represents the product/cushion.

Figure 4.23: A schematic of the lifting mechanism. This is a side cross-section view of the space surrounding the product. On top is seen the two panels which cover the top of the space. The red lines represent the length of the strap between the hinge point and the cushion/product. $b$ is the distance from the outer edge of the panel to the strap hinge point. $c$ is the distance from the top of the product to the panel. $x$ is the distance from the bottom of the hole to the top of the product. $h$ is the height of the product. $w$ is the width of the product. $t$ is the thickness of the moving panels. $\theta$ is the angle between the moving panels and the vertical wall of the hole. $b_w$ is the width of the hole. $b_h$ is the height of the hole.

across two opposite panels (red). These have mirrored motion so as they open, the strap is pulled up equally on both sides. It was desired to achieve the largest amount of lift possible, however, as the model was configured for the maximum amount possible, interference was observed between the top panels and the product which prevented it from opening. Figure 4.22 shows a cut-away of the assembled box and Figure 4.23 shows a schematic of some of the factors involved in this problem. The equations are given in Equations 4.1 and 4.2.
The lift is given by

\[ d_{lift} = x_f - x_i \]  \hspace{1cm} (4.1)

which is equivalent to

\[ d_{lift} = 2t + b + c - \sqrt{b^2 + c^2} \]  \hspace{1cm} (4.2)

For more on this, see the spreadsheet titled “BoxLiftMech.xlsx”. In this file, not only is lift considered, but so is interference with the top panels.

4.2.5 Prototypes

After selecting the concept, the team progressively iterated on the design. Following is a set of images showing the progression.

![Figure 4.24: The paper model in the closed and open positions.](a) (b)

Figure 4.24: The paper model in the closed and open positions.
Figure 4.25: The initial OPT concept model in the closed and open positions.

Figure 4.26: An early prototype of the box in the closed and open positions.

Figure 4.27: A prototype of the box in the closed and open positions.
4.2.6 Conclusion

Significant Insights

A considerable amount of understanding and insight was gleaned during the creation of the watch box as has been discussed throughout the preceding sections. However, two distinct insights will be highlighted here. First, it was learned that origami based design proves particularly difficult because both the open and closed positions of the piece must be considered as well as the motion that occurs between the two. This requires the design to accommodate interference of
different panels as the product moves through its assigned motion. Secondly, building origami structures with rigid materials often requires tight tolerances. If precision placement of hinges and panels does not occur, the origami will not deploy appropriately. Flexible materials are very forgiving, they generally allow for fairly loose tolerances while rigid materials do not provide this convenience.

Results

Based on both the requirements presented in Problem Definition and Requirements and feedback received by the team, an origami watch box was successfully developed. The box appears to be a normal watch box when closed, making it intuitive to use. During the opening process, though, is when the unique motion catches the eye of the opener as it reveals the seemingly levitating timepiece. The box is stable in both the open and closed positions and the dimensions of the inner area for the product match those specified by our customer. The outer dimensions are similar to those given. Not only did the box meet these criteria, but it did so while having an elegant and beautiful appearance.

Moving Forward

There is considerable room for continued development and refinement on the watch box. Foremost among these is design considerations for manufacturing and cost. Eliminating the total number of pieces used in the box construction would cut down on tooling and material costs. This could be accomplished by using 6.35 mm material in place of the current 3.175 mm. The lifting mechanism could also be redesigned with an emphasis on implementing more height to the lift. This would most likely require a completely new mechanism as the potential of the lifting strap has been nearly maximized. Lastly, added precision in the assembly of the hinge construction to the rest of the box would improve the overall functionality of the box as it is opened.
4.3 Kisakuna (Kinetic Sculpture)

4.3.1 Background and Objective

The objective of this project was to develop a large kinetic sculpture to be displayed in the origami exhibit of Brigham Young University’s Museum of Art. While most of the exhibit consisted of artistic origami creations by some of the world’s top origamists, the exhibit would also include a room dedicated to work done by the Compliant Mechanisms Research group. The kinetic sculpture would serve as a transition piece between the art of origami and the engineering of it.

4.3.2 Requirements

The requirements for the ideal result of this project were identified and include:

- The sculpture should open and close completely
- The sculpture should be interactive
- The sculpture should be easily actuated
• The sculpture should be safe for the patrons
• The sculpture should be beautiful
• The sculpture should be robust
• The sculpture should be large
• The sculpture should have a single DOF (degree of freedom)
• The sculpture should employ the offset panel technique (OPT)

4.3.3 Discussion of Final Design

Origami Inspiration

During concept generation and an exploration of potential fold patterns for the sculpture, the square twist (as shown in Figure 4.31(a)) became a top candidate due to its intriguing twisting motion and its simplicity. Once selected, several small scale models of the square twist pattern were built to identify potential inversions. It was decided that the bottom middle panel would be grounded because this would exaggerate the unique twisting motion as demonstrated in Figure 4.32.

Sculpture Materials

The materials and their properties were a driving factor in this design. They would determine to what degree the sculpture would be feasible for fabrication, safe, aesthetic, etc. After much exploration and experimentation with both panel and joint materials, GatorFoam was selected for the panels/offsets, MDF for the grounded panel, and canvas for the hinges.

Besides its strength (as demonstrated in Figure 4.33) and weight properties, GatorFoam had many desirable traits - it was easily accessible, easy to machine, easy to paint, and allowed for strong bonds with many types of adhesives. After a sheet of GatorFoam was painted, the panels and offsets were cut out of the sheet with a CNC router. The panels and their offsets were then joined with an adhesive to complete the panel subassemblies.
Figure 4.31: The crease pattern used as the base of the kinetic sculpture was the square twist. In (a) is shown the crease pattern and assignment and in (b) is a photo of the sculpture in which the pattern is easily seen.

Figure 4.32: An illustration of the motion of the kinetic sculpture.
Figure 4.33: GatorFoam was selected because of its strength and its light weight.

Figure 4.34: An early version of the stitch type canvas hinge.

The hinges consisted of two laser-cut rectangles of canvas and a stitch sewn down the center as seen in Figure 4.34. The completed hinges and an industrial strength glue were then used to connect the panels.

**Actuation**

The actuation of the kinetic sculpture was a challenge of its own. Initially, the idea was to make the sculpture hand-actuatable. However, this would likely introduce a large amount of variation in the actuation so a more consistent and predictable mechanism was chosen.
The selected actuation method called for a motor and pulley system to lift the weight of the sculpture and a simple switch system to control the direction of the motor. This method is shown in Figure 4.35. The actuation started with the user pressing the actuation button. When the microcontroller on the PCB received this signal, it sent a signal to turn the motor which turned the spool, reeled in the cable, and hoisted the sculpture. As the cable retracted inside the upright of the stand, the upper cable stop, which was rigidly attached to the cable, approached the direction switch, which was fixed to the stand. The motor stopped once the cable stop flipped the direction switch. The positioning of the cable stops is how the open and closed positioned were controlled.

Once the actuation button was pressed again, the motor ran in the opposite direction and the weight of the sculpture pulled the cable back out of the spool. When the lower cable stop flipped the direction switch, the motor stopped and the system was in position to be actuated again.

Two separate problems emerged which prevented the sculpture from opening and closing completely during actuation. From these problems stemmed two creative solutions. First, in the crease pattern there is a vertical crease that divides the pattern in half. This existed as a hinge in the sculpture and prevented it from opening all the way (refer to Figure 4.31). Since the center

Figure 4.35: A diagram of the actuation method for the kinetic sculpture; (a) shows the closed position and (b) shows the open position.
panels, which together form a square, were coplanar in both the open and closed positions of the sculpture and had a minimum dihedral angle of approximately 90 degrees, a compliant spring made of polypropylene was employed to combat the issue. This spring is shown between the panels in Figure 4.36. Since the spring worked against the closing of the sculpture, this solution required some analysis and experimentation to determine the spring dimensions which would best aid in opening and allow for closing. Second, due to the weight of the panels, the sculpture would not close completely. To fix this, a counter weight was inserted into one of the panels and the other end of the weight’s line was fixed to the adjacent panel as illustrated in Figure 4.37. When closing, this counter-weight successfully pulled the sculpture closed. Some optimization went into the length, weight, and positioning of the counter-weight.
Figure 4.38: The assembled stand for the kinetic sculpture.

**Stand**

The stand was the integrating piece of the design. The sculpture was fixed to it, the motor and PCB were also mounted to it, and the cable ran through it. It was important, though, that the stand not only be functional, but that its aesthetics matched that of the sculpture and the gallery. The base of the stand was designed to mimic the square in the center of the sculpture and the uprights were given an angled look. After the parts were machined, they were painted to match the gallery walls and assembled. Figure 4.38 shows the stand assembly before it was painted.
4.3.4 The Exhibit and Continuing Challenges

The design iteration did not, however, cease once the exhibit opened. Many times throughout the five-month-long exhibit, problems surfaced and prompt solutions were required. Following is a brief description of some of the main problems that emerged.

Poor Adherence

A certain box joint between a panel and its offset experienced a large amount of torque and stress. This joint separated multiple times as demonstrated in Figure 4.39 and eventually required screws to hold it together.

Loose Cable

Another issue that occurred repeatedly during the early weeks of the exhibit was caused by the circuitry which delayed the stop of the motor after the sculpture closed. Often, this resulted in the cable becoming loose and even derailing from the spool. This brought on a host of other problems. After a handful of failed attempts to solve this problem, it was solved by the addition of a cable tensioner to the design. This tensioner, as depicted in Figure 4.40, would take up any slack in the line and keep the cable tight on the spool.
Figure 4.40: The cable tensioner that was added to the kinetic sculpture. In (a) is shown a photo of the mechanism, (b) illustrates the mechanism during normal operation, and (c) is an illustration of the mechanism when the stop of the motor has delayed and the tensioner has taken up the slack.

Figure 4.41: A illustration of how we fixed the issue of the breaking cable. On the left is shown the sharp edge which caused the problem and on the right is the chamfered edge.

**Broken Cable**

Lastly, the sculpture’s cable broke twice as a result of a sharp edge on one of the cable stops. This cable stop was required to travel up and over a pulley and over time the sharp edge wore through the cable. To fix this, the sharp edge of the cable stop was chamfered (see Figure 4.41).

**4.3.5 Prototype Progression**

Following is a series of images (Figures 4.42 - 4.46) showing the progression of the prototypes for the sculpture.
Figure 4.42: The first conceptual prototype of the kinetic sculpture.

Figure 4.43: A half scale prototype of the kinetic sculpture. In the open position, this is 4’x4’.
Figure 4.44: The first full-scale (8’x8’) prototype of the kinetic sculpture. Made with 3/8” foam board.

Figure 4.45: A 1” thick full-scale prototype of the kinetic sculpture.
4.3.6 Conclusion

The kinetic sculpture was a popular piece and, with some repairs, it endured thousands of cycles and the entire five-month-long exhibit. The sculpture was safe, beautiful, and fulfilled the requirements listed in Requirements. As a result of the project, significant insights were gained into building OPT models, actuating OPT models, and some limitations of the OPT.

4.4 Monolithic OPT Models

Since the OPT preserves both an origami pattern’s kinematics and the range of motion, it may seem superficially that it is a simple one-size-fits-all solution to thick origami. This is not the case, however. With these benefits of the OPT come several disadvantages. For example, once a designer has chosen to use the OPT rather than a less complex thickness accommodation method, the design time required for even a simple model is greatly increased as well as is the manufacturing and assembly time.

The majority of the OPT models that exist require the manufacturer to cut many panels and offsets from a monolithic sheet, adhere the offsets to their respective panels, and finally assemble
the panel-offset sub-assemblies. In this process, there are many opportunities for error. For example, which offsets go with which panel, in which direction do they extend from the panel, which sub-assembly attaches to which, and how should the hinges be made. All of these are mistakes that I still make.

To combat this issue, an exploration has been initiated into creating an OPT model from a monolithic part - panels, offsets, and hinges included. While this method has its own set of challenges, it has the potential to greatly reduce both the time required for and the opportunity for error in manufacturing and assembly.

4.4.1 Designing a Monolithic Model

The idea behind the design of such a model is simply to flatten an OPT model, offsets and all, such that all of the hinges lie on one side of the monolithic material. In the models that have been created, SolidWorks sketches were used. In order to achieve a parametric design, global variables were created for the material thickness. This parameter is very important for these
models. To start, the hinge(s) which lie on the models joint plane are left coincident (the vertical line between the bottom panels in Figure 4.47(b)). From this point, fold back everything and add appropriate spacing to complete the design. See the simple model in Figure 4.47 as an example.

4.4.2 The Fabrication for a Monolithic Model

The steps taken to make the model shown in Figure 4.48 were as follows:

1. Create the sandwich material as shown in Figure 4.49 by adhering a sheet of foil to the panel material and the hinge material to the other side of the foil. The foil acts as a mask and prevents the laser from piercing the hinge material.

2. Laser cut the pattern for the panel material as shown in Figure 4.50.

3. Remove excess material from around the pattern as shown in Figure 4.51 and from inside the pattern as shown in grey in Figure 4.47.

4. Cut through the hinge material at the outer edges of the material. The result is the monolithic model as shown in Figure 4.52.

5. Fold and adhere the offsets where needed as shown in Figure 4.53.
Figure 4.49: The layers in the sandwich board for a monolithic OPT model.

Figure 4.50: The monolithic pattern cut into the panel material.
Figure 4.51: Remove the excess material from around the pattern.

Figure 4.52: Cut the outline of the pattern through the foil and hinge material.
This model was created from a simple single-vertex pattern, but this concept has the potential to reach more complex patterns. For example, see the hinge mechanism in the origami watch box which has at least two vertices and not only uses the Tyvek as a hinge, but to cover the panels as well.

4.5 Other Applications and Examples

4.5.1 Deployable Parabolic Antenna

Three traits of the OPT (and thick origami in general) make it a strong candidate for things such as deployable antennas. First is the capability to use suitable rigid materials with deployable origami patterns. Second is the fact that the geometry of each panel can easily be altered to have the needed shape, i.e. parabolic. Last is the single-DOF characteristic of rigid-foldable single-DOF patterns made thick with the OPT.

In this conceptual model, the square twist (illustrated in Figure 4.54) was used to design a parametric parabolic antenna. Even though this model is made up of several panels which are all offset from each other, each panel forms a parabolic shape with a shared focal point. The model is parameterized by the ratio of the focal distance to the diameter \( F/D \) of the pattern. In this design, the thickness of a panel is a function of the thickness of the panels between it and the joint plane as well as its distance from the focal point. With a small \( F/D \) ratio, the outer edges of the panels
Figure 4.54: This square twist pattern was used to create this foldable parabolic antenna.

Figure 4.55: An antenna with $F/D$ ratio equal to 1. This results in a thick model of this antenna. The focal point is indicated by the point at the end of the dotted line.

need to extend significantly high to achieve the parabolic shape. This means that the panels and the system will be much thicker than a similar system with a large $F/D$ ratio. This can be observed when comparing the antenna with a $F/D$ ratio of 1 in Figure 4.55 to the antenna with $F/D$ ratio equal to 2 in Figure 4.56.
Figure 4.56: An antenna with $F/D$ ratio equal to 2. This results in a thin model of this antenna. The focal point is indicated by the point at the end of the dotted line.

Figure 4.57: A 3D printed Octocube which is printed in only 4 parts and snaps together.

4.5.2 3D-Printed Octocube

The Octocube is a thick origami toy that uses the OPT [13]. After the meticulously assembly of dozens of acrylic pieces to make an octocube, it was clear that 3D printing would be a more efficient method to fabricate this mechanism. Figure 4.57 shows the final design of the 3D printed Octocube which was printed in 4 parts and then snapped together to form the final assembly.
4.5.3 Reconfigurable Geometry

To demonstrate the almost arbitrary assignment of geometry to OPT panels, this Lego model was created. Its origami base was 3D printed and a thin layer of Legos were glued to it. This created a simple OPT model with reconfigurable geometry. In Figure 4.58 is shown a configuration with arbitrary geometry and in Figure 4.59 is shown the same model having a configuration which folds up to resemble a man with a top hat.
Figure 4.60: This square twist pattern was used to create the reduced panels model.

### 4.5.4 Reduced Panels

As a demonstration of an extreme change to a panel’s geometry, this square twist model was built with some of the panels essentially removed. Since the rotational axes determine the behavior of an origami mechanism, the rotational axes were left untouched while four of the pattern’s panels were virtually eliminated (shown in grey in Figure 4.60). In the model shown in Figures 4.61 through 4.63, it was almost coincidental that the four trapezoidal panels together were bordered by all of the pattern’s axes. This allowed for a simple model in which the five remaining panels were designed as prescribed by the OPT and the removed panels were assigned a thickness of zero. The axes and their corresponding sleeves were then added. This concept has potential for applications which may require thin systems or specific shapes.
Figure 4.61: A square twist OPT model with four of the nine panels removed in the closed position.

Figure 4.62: A square twist OPT model with four of the nine panels removed in an intermediate position.

Figure 4.63: A square twist OPT model with four of the nine panels removed in the open position.
CHAPTER 5. CONCLUSION

While applying origami to thick materials continues to be a challenge, the work described in this thesis has made significant progress in bridging the gap between engineering materials and the effective application of origami. This work uncovers some of the potential held by the OPT, provides a comparison of the OPT to other thickness accommodation methods, demonstrates the implementation of the OPT, and articulates principles for implementing the OPT in a design. Through the efforts described in previous chapters, the objectives of this thesis were met.

The OPT is compared to other thickness accommodation methods in a table based on several characteristics that are key to thick origami models, including whether or not kinematics are preserved, if the range of motion is preserved, and whether or not the model has a single-DOF. Additionally, several applications are demonstrated throughout the thesis. Some of these include an origami-based watch box, a large kinetic sculpture which was on display at a museum, a full-size folding table based on an origami pattern, and a foldable circuit board. The applications take advantage of the capabilities listed above. In Appendix A, is a list of links to online videos, including an instructional video for how to use the OPT and others which demonstrate the concept of the OPT through animations and application examples. While these are accessible to all, most can only be viewed using the provided links. Significant effort went towards expanding our understanding of the OPT. A summary of the findings follow in the next section.

5.1 Implementing the OPT

Through the design and fabrication of dozens of OPT models and applications, a significant amount of insight has been gained into developing applications using the OPT. Following is a summary of things which can be considered in the design of an OPT application. These considerations are valid for both market pull applications (an application in which the need is known
and the solution is sought) and technology push applications (an application inspired by a new technology).

- Fold Pattern - There exist many rigid-foldable patterns which can be made thick using the OPT. These have unique motions and configurations which could lend each to certain applications. One is not limited, however, to the existing patterns as they can all be modified and new patterns emerge regularly. While the selection of a fold pattern may seem like the first step in developing an OPT application, it is suggested that a variety of patterns be explored using some of the following considerations.

  – Motion - In origami-inspired design applications, motion, open/closed shapes, or both motion and shapes usually motivate the use of origami. Observe closely a pattern’s motion. What is unique about its behavior? In the development of the kinetic sculpture, an aesthetic motion was desired. This was eventually found by grounding different panels of the square twist pattern. The design of the watch box called for an aesthetic motion that could also be an opening motion. This was found in the selected pattern while exploring different versions of the square twists (refer to Figure 4.8).

  – Open and Closed Shapes - In some models, the motion is not as important as the shape of the mechanism in its extreme positions. Deployability is often a sought-after trait of origami and is a subset of this idea. For example, the circuit board benefits from being compact in the closed state and much larger (about 9 times) in the open state. The toolbox serves as another example. Four of the panels in the selected pattern were observed to remain parallel to the table. These panels also had the same locations in both the open and closed positions relative to the table. These two observations of the pattern’s motion facilitated the addition of both the compartments and the walls.

  – Symmetry - If a fold pattern has symmetry about a fold or collinear folds, its OPT model can be significantly simplified. While the kinematics of the model will technically be different, the general motion stays the same while allowing the offsets to be much shorter. This is discussed in depth in Chapter 3.

  – Four-Thickness Models - Many rigid-foldable patterns have panel stacks of only four material thicknesses. Such patterns are convenient because, when the joint plane is
placed such that two panel thicknesses are on each side, they will not require any clearance holes in panels to avoid interference with offsets. This means that, normal to the open zero-thickness model, the model will appear to be solid and uninterrupted. This could be desirable in some applications.

• Geometry - The shapes of both the panels and the offsets can be modified to meet the requirements of a given application. Refer to Chapter 2 for more discussion on these points.

  – 2D Profile of Panels - One of the simplest ways to alter the geometry of a panel is to change its profile, or its shape in the origami pattern. See, for example, the panels of the folding table in Figure 2.14 and the blue and green panels of the watch box in Figures 4.15 and 4.16.

  – Panel Thickness - The OPT accommodates thick materials, but it also allows for separate thickness assignments for panels. Some panels in a model can be given a very large thickness while others have no thickness at all. This can best be seen in the concepts generated for the watch box in Figure 4.14, the lift in Figure 2.15, and the reduced panels model in Figure 4.63 where some panels were assigned zero thickness.

  – 3D Panel Geometry - Not only can the panel thickness vary, but the panels do not need to be sheet-like, they can take on a wide range of three-dimensional shapes. See the folding sphere in Figure 2.8 and the watch box panels which form the base and lid in Figure 4.21. More examples can be found in [13].

  – Offset Geometry - While the panels might provide the most obvious opportunity to modify geometry, the shapes and positions of the offsets of the panels can also be greatly altered. In the origami-inspired lift as shown in Figure 2.15, the offsets do not have the same sheet-like shape that most of the other models do. Instead, they cover most of the inner face of the outside panels. Also, as shown in Figure 4.6, the watchbox has some offsets that extend the entire length of panels. Lastly, some of the offsets of the toolbox were given a position along their axes such that interference was avoided.

• Materials and Panel Fabrication - Most of the models presented in this thesis use sheet materials. However, virtually any material and even multiple materials can be used to make an
OPT model. A panel material and fabrication method suitable to the application should be identified. This is discussed in Chapter 2.

• Panels With Purpose - Panels can be designed to serve purposes other than just linking rotational axes. Think about the purpose of the application at hand. For example, does it require mechanical or electrical components or need to contain a fluid? These design requirements can often be worked into the design of the panels. Two simple examples are the lifting mechanism of the watch box as illustrated in Figure 4.22 and the counterweight inside of the panel of the kinetic sculpture as shown in Figure 4.37. Panels could include more complex mechanisms such as motors, circuitry, pulley systems, display screens, flipping/moving parts, wheels, etc.

• Joint Plane Location [13] - The location of the joint plane has a large impact on (1) the motion of an OPT model and (2) the length and number of the offsets in a model. In most of the models presented in this thesis, the joint planes were assigned a location in order to simplify the model as much as possible. However, if a certain motion is desired, the location of the joint plane can be optimized to achieve that motion.

• Hinges - The strength, fabrication, stiffness, extension, size, etc. of hinges depends on a given application. Several different styles of hinges can be seen throughout this thesis. See the canvas hinges in the kinetic sculpture in Figure 4.34, the metal hinges in the table in Figure 2.14, and the 3D-printed snap-together hinges in the octocube in Figure 4.57.

5.2 Future Work

I recommend the following topics for further exploration in order to expand the use and value of thick origami.

• Applications based on patterns other than the square twist. In Chapter 3, I have shown several patterns which exhibit characteristics showing potential for application. In addition to these, there exist many more rigid-foldable patterns that could be experimented with.

• While the OPT is useful, I do not believe that it is as efficient as it could be. The fabrication and assembly of OPT designs requires significant amounts of time. I have done some
preliminary conceptual experimentation with monolithic OPT models that shows potential to be applied to more complex models.

- The design of OPT models is also fairly slow and tedious. While I have been able to improve methods of designing these, it may be desirable to create software with the ability to generate them automatically.
REFERENCES


APPENDIX A. VIDEOS

A.1 Chapter 1

Spherical Mechanism Animation - https://youtu.be/oLu0_-CPJXk
OPT Animation - https://youtu.be/4CP6pNPtkMs
OPT Instructions - https://youtu.be/OnwQERuYSm0

A.2 Chapter 2

Kinetic Sculpture - https://youtu.be/5e28J066oGY
Toolbox - https://youtu.be/IFQv42ldn14

A.3 Chapter 3

Bird Base - http://youtu.be/dKvmgBV96NQ
Yoshimura - http://youtu.be/JpAeP18mCq8

A.4 Chapter 4

Toolbox - https://youtu.be/IFQv42ldn14
Watch Box - http://youtu.be/XN6KodxYQzk
Watch Box Fabrication - http://youtu.be/IlWT0fqTsXM
Kinetic Sculpture - https://youtu.be/5e28J066oGY
Monolithic Model - http://youtu.be/6-rIX3PhJRU
3D-Printed Octocube - http://youtu.be/Nu4-6uXeX2g
Reduced Panels - https://youtu.be/9I8j_0EUDEI