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# CONSIDERING MANUFACTURABILITY IN THE DESIGN OF DEPLOYABLE ORIGAMI-ADAPTED MECHANISMS

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## ABSTRACT

*Primary barriers to greater implementation of deployable origami-adapted mechanisms are their manufacturability and robustness. This paper discusses manufacturability in the design of such mechanisms through presenting and examining three examples. Manufacturability lessons gathered from these examples include the importance of joint-panel interfaces and how techniques and approaches for origami-adapted design can be customized to meet the needs of a specific product. As the manufacturability of deployable origami-adapted products is addressed and improved, their robustness will also improve, thereby enabling greater use of origami-adapted design.*

## 1 INTRODUCTION

Origami has been increasingly applied in the realms of engineering, technology and mathematics. This ancient art of paper folding has found applications ranging from heart stents [1] to solar arrays [2] to kayaks [3]. Origami patterns that allow for movement are often well suited to application in engineering designs that require motion or the ability to collapse for compact storage. Such designs include many aerospace mechanisms where deployability is advantageous, if not necessary. Designs and products that do not directly apply an origami pattern but rather modify or adapt the pattern while still maintaining functionality are classified as origami-adapted [4]. One example of a deployable origami-adapted mechanism is shown in Figure 1.

This paper aims to improve the robustness of deployable origami-adapted mechanisms by examining the manufacturing concerns associated with these mechanisms. As these concerns are addressed, a gateway is created to better origami-adapted deployable mechanisms that are more robust and easier to manufacture. Improving their robustness will lead to better deployable mechanisms that are suitable for use in more aerospace applications. This will enable the aerospace industry, including NASA, to accomplish things that were previously unattainable through the ability to use volume on spacecrafts more efficiently and have mechanisms with new useful functions that are robust and reliable.

Though several approaches have been developed to apply origami in materials that are not paper-like, issues still remain that hinder widespread use of origami-adapted design. Methods and techniques for accommodating thickness have been developed in response to the need for means to apply origami patterns using materials that cannot be approximated as having zero thickness, like paper [5]. Most of these thickness-accommodation techniques complicate manufacturing [6, 7] through high part counts, making many origami-adapted designs less practical and robust than designs that do not utilize origami. Key to the approaches is that the motion at creases in paper origami must be translated to "hinges" in thick origami. The challenge lies in finding a feasible fabrication approach that allows for efficient assembly of the product, yet still meets all the necessary motion and other design objectives. By addressing the fabrication concerns associated with deployable origami-adapted products, the robustness of these products can be improved.

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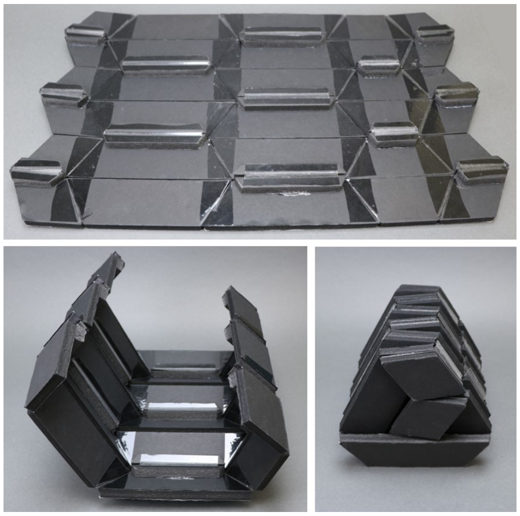


**FIGURE 1**: Origami-adapted mechanism shown flat, partially folded, and folded.

The choices involved in deciding how to translate the motion at creases in paper origami to thick origami pose a significant barrier to successful implementation of origami-adapted designs. Ideally, an origami-adapted product would be manufactured from a single sheet of material. If the panel material is not conducive to compliant hinges, the entire origami pattern cannot be made of a single sheet of material. One such class of materials is metals; though metals can be in sheet form, they are not easily creased to create "hinges" that allow repeated motion [8]. Also, not all thickness-accommodation techniques allow for fabrication approaches that use a single flat sheet of material, such as stamping and laser cutting. For example, the offset-panel technique [9], which modifies the panel geometry through the addition of offsets to avoid panel interference, does not allow for fabrication using a single process because of the offsets.

High design complexity stemming from translating creases to hinges leads to low robustness in origami-adapted products. High part count in a design causes high complexity. Depending on the hinge choice, it is possible to have as many parts as there are faces and creases in the origami pattern. This high part count results in a large number of interfaces between parts. It is not uncommon for several panels in a pattern to have three or more interfaces. Each interface becomes a place where alignment error can be introduced, thereby causing a significant tolerance stack-up over the whole product. Consequently, the robustness of the design suffers as the likelihood of joints binding or becoming too sloppy for proper functionality and deployment increases.

Because of all of the problems associated with hinges, many origami-adapted designs have not made it past the prototyping stage. The one-off prototypes made of foam board and tape make the issue of robustness apparent in all but the highest construction quality prototypes. These tape hinges do not usually translate well to final designs because hinges made of tape do not have sufficient performance for most applications.

There is a need for a clear way to address the manufacturing requirements of an origami-adapted product during the design phase. Improving the manufacturability of the design will lead to a more robust product. This paper reviews and summarizes ways that manufacturability can be approached in the design of origami-adapted products.

## 2 EXAMPLES

This section reviews three examples of how manufacturability can be considered and the role it plays in the design of origami-adapted products. The first example is a manufacturing process that was developed to improve the manufacturability of fabric-based origami-adapted products. The second and third examples illustrate how manufacturing was considered for design of an origami-inspired ballistic barrier and two sheet metal origami mechanisms, respectively.

### 2.1 Manufacturing Process for Fabric-based Origami-adapted Products

*Sandwich molding* is a traditional process that is used for creating highly complex pleats in fabric. The current sandwich molding process involves creating complex molds by hand based on unfolded origami patterns. The molds are made from a stiff laminate and the pattern is made twice, creating two halves of a single mold. A piece of fabric is then placed in the mold and then the assembly is refolded. This assembly is then placed in an oven. Once cooled, the molds are removed from the fabric, leaving the pattern imprinted in the fabric. Due to the complexity of this process, each item is assembled, folded and removed by hand. The patterns that can be made are complex, but the requirement that each piece be handmade limits the scale of production and leaves many opportunities for errors. [10]

Pleat rolling is an industrial scale process used to manufacture patterned materials. The fabric or paper is put into a roller that crimps the material as it passes through, such as seen in the patent from Painter et al. [11]. Pleat rolling can produce large amounts of a simple pattern, but lacks the ability to create complex patterns yet.

For this example of origami and manufacturing, a manufacturing process is explained that was designed to have the same technical capabilities as sandwich molding in addition to being scalable to meet the demands of large scale industrial orders. By creating a two part mold that describes a partially folded pattern, it is possible to effectively stamp the material with the full pattern and set the default relaxed state of the material.

The steps of this manufacturing process, which is here called the *double mold* process, are as follows:

**FIGURE 2**: Two identical mold halves used for creating a Miura-ori pattern using the double mold process shown open and together

1. Mold: Design and machine the mold, consisting of two halves that mesh together, out of high density urethane foam (ex.: see Fig. 2).
2. Sandwich/Clamp: Sandwich the fabric between the two mold halves and clamp this assembly of the mold and fabric together to apply pressure. Preheating the molds before assembly and clamping aids the heat distribution during the heat-setting step.
3. Heat-set: Place the assembly in an oven for 30 minutes at 300°F to set the crease pattern in the fabric.
4. Cool: After removing from the oven, cool the assembly. Cooling time necessary will vary depending on the size of the molds and environment used for cooling; a large mold that has base dimensions of 12” by 12” requires approximately 2 hours in a refrigerator.
5. Release: Release the clamps and remove the finished patterned fabric.
6. Second Heat-set (optional): If a further folded set position is desired, fold the fabric to the collapsed configuration using the pattern already set in the fabric, then clamp the folded fabric between two pieces of a flat rigid material such as cardboard or metal (that can withstand the temperatures required for heat-setting the fabric). Then repeat the “Heat-set”, “Cool”, and “Release” steps.

A sample of fabric that has been heat-set using the double mold process (not including the optional second heat-set step) can be seen in Figure 3. This process has given the best results when using 100% polyester fabrics. Figure 4 shows a potential application for the double mold process: a reusable shopping bag that was heat-set once to imprint the pattern, fully folded using the pattern, then heat-set a second time to make it easier to fully collapse and roll up the bag for neat and compact storage.

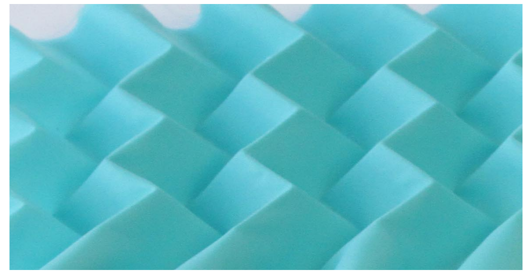


**FIGURE 3**: A sample of fabric that has been heat set using the double mold process with the mold shown in Fig. 2

**FIGURE 4**: A reusable shopping bag that has been heat-set using the double mold process (including the second heat-set step) that can be easily rolled up after collapsing the origami pattern for simple storage.

There are a few key characteristics of the double mold process. One important characteristic of the process is that it allows for setting the default state of the material to an intermediate fold state, rather than completely folded or completely unfolded. There is, however, still the option of doing a secondary heat-set to set the default state at the completely folded state. This ability to have an intermediate fold state as the default may be very useful, if not necessary, for some applications. Another characteristic is that the process has the capability of working for complex origami patterns, not just simple pleats, while being a more scaleable process than the traditional sandwich molding process that requires a great deal of time and skill.

**FIGURE 5**: Origami-inspired ballistic barrier in the deployed state.

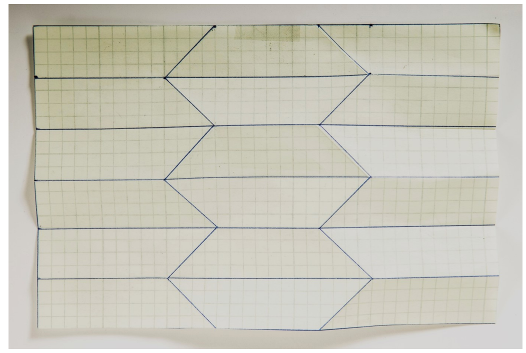


**FIGURE 6**: A modified Yoshimura pattern used for the design of an origami-inspired ballistic barrier.

### 2.2 Ballistic Barrier

In addition to providing ballistic protection, the origami-inspired barrier shown in Figure 5 was designed to be portable, deployable, and self-standing. For anything to be deployable, it must have hinges, joints, or some other way to allow for the deploying motion. As a good ballistic barrier ought not to have any significant weak areas, use of joints such as traditional hinges posed serious weaknesses that could be difficult to mitigate while maintaining portability. Therefore, using ballistic fabrics, such as the aramid fabric Kevlar, as the material to provide both ballistic protection and motion at the joints made the most sense because such fabrics can also be flexible to allow for the necessary motion of deploying the barrier.

Manufacturability was a characteristic considered during selection of the origami pattern for use in the ballistic barrier design. The origami pattern selected can affect such characteristics as part count of the mechanism, what methods may be feasible for assembly and the order in which manufacturing operations can be done. The modified Yoshimura pattern that was chosen for the barrier (seen in Figure 6) has a moderate number of panels while still meeting the stability and deployability design requirements.

A key challenge resulting from the use of fabric as the primary material for the barrier that involved considering manufacturability was how to make areas of the fabric rigid to be the panels of the origami pattern while still allowing for the flexibility necessary at the creases. Because the barrier design required twelve layers of aramid fabric, the layers must be bound together for function as a single mechanism. Many different methods of assembling fabric layers and achieving rigidity with local flexibility were explored and prototyped to determine a suitable method. A light rigid material was cut into panel shapes to give rigidity to the panel areas of the origami pattern.

The membrane thickness-accommodation technique [2] was used as a basis for determining how to accommodate for thickness in the barrier. However, the membrane technique alone was not sufficient for accommodating the thickness of the barrier because the membrane technique assumes that the "membrane" connecting the panels has negligible thickness as compared to the panels. The twelve layers of aramid fabric together were approximately twice the thickness of the center panel material being used, thereby not allowing for use of the membrane technique as it has been previously described in [2].

Another issue that arises when folding several layers of such fabric is that, if all layers have the same length of "folding section", then the fixed length of the outermost layer causes bunching of the other layers as the radius around which they fold becomes smaller towards the inside of the fold. To address this, concepts from the strained joint technique [12] were used in conjunction with the membrane technique. By drawing upon both thickness-accommodation techniques, a different approach was developed that consisted of sandwiching the rigid panels between the layers of aramid fabric, six fabric layers on each side, and leaving sufficient space between the rigid panels for the fabric layers to fold. The gap between the panels provided space for the fabric to fill as it bunched during folding, thereby reducing the effect of bunching on the motion of the mechanism.

To bind all the layers of the mechanism together, a spray adhesive was used to bond the fabric layers together and to the rigid panels. The adhesive used was 3M™ Super 77™ Multipurpose Spray Adhesive. One advantage found when using a spray adhesive that never fully hardens is that some push and pull between the fabric layers can occur during initial folding of the mechanism. Therefore, the spacing between the rigid panels during fabrication does not require overly strict tolerances to still result in a functioning mechanism.

### 2.3 Sheet Metal Panels

Sheet metal manufacturing processes provide different capabilities on which manufacturing approaches can be based. A common and economical sheet metal process is bending. The "bent" panel approaches shown in Table 1 have been developed to take advantage of this process for origami-adapted mechanisms using sheet metal panels [13].

Figure 7 shows a mechanism that is based on the square twist origami pattern. The mechanism uses the hinge shift technique to accommodate for thickness and the associated bent panel approach to allow for use of sheet metal as the panel material. The design of the panels using the bent approach is not trivial as it requires careful consideration of where the panel material must be located to allow for the necessary interfaces with other panels while also avoiding intersection with other panels during the mechanism's motion. The information needed to properly design the panels can be obtained from the thick origami model just created by accommodating for thickness using the chosen thickness-accommodation technique (not specifically considering sheet metal).

Shown in Figure 8 is another sheet metal mechanism. This mechanism, however, uses the Miura-ori tessellation as the base origami pattern and the tapered panels technique for accommodating thickness. This mechanism is somewhat simpler as each panel requires only an offset bend for the panel material to match the interfaces. However, another consideration of using a bent panel approach with the tapered panels technique is that panel material at the vertices must be cut away. If the material surrounding the vertex is not removed, then the mechanism will fail to function because of interference occurring between the panels.

In both of these sheet metal mechanisms, tolerances during assembly were a significant concern. Both the Miura-ori tessellation and square twist patterns are overconstrained by geometry. If it were not for the symmetry that exists in the patterns, the mechanisms would have zero (or negative) degrees of freedom, therefore not allowing for any motion. To avoid binding of any of the hinges due to misalignment, the assembly of the hinges and panels was completed very carefully to ensure adequate tolerancing for the assembly to function.

## 3 MANUFACTURABILITY LESSONS

From the examples reviewed in the previous section, several lessons concerning manufacturability in origami-adapted mechanisms can be gathered. Some lessons are seen from the specific examples, whereas others can be gathered by examining more than one of the examples.

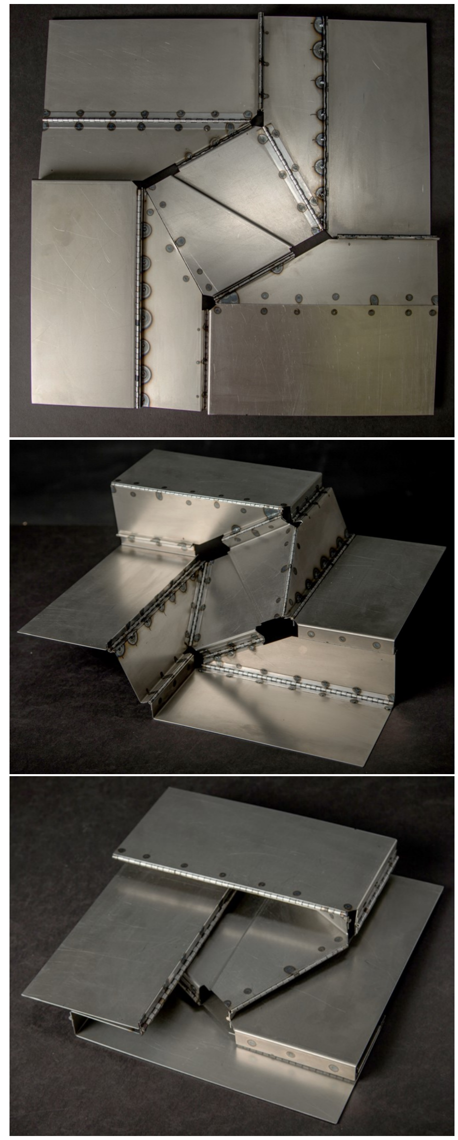
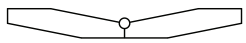
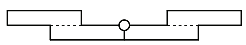
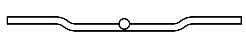
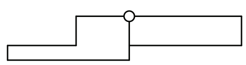
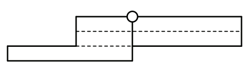
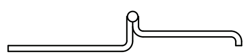


**FIGURE 7**: Sheet metal square-twist mechanism designed using the hinge shift technique shown unfolded, partially folded, and fully folded

One lesson from the example of a manufacturing process for fabric-based origami-adapted products (Sec. 2.1), is that another viable way for modifying and processing sheet goods is by heating. This can be particularly useful when trying to impart patterns to fabrics and such materials that can be heat-set. Heat-setting, using a process such as the double-mold process, can also be used when an intermediate fold state, rather than the fully folded or unfolded state, is desired as the default state of a product. A key lesson from the ballistic barrier example (Sec. 2.2) is that thickness-accommodation techniques can be customized

**TABLE 1**: A comparison of panel approaches for two thickness-accommodation techniques for origami-adapted mechanisms. In the second column, dashed lines indicate layer divisions within the panels and small circles represent stock hinges. *Part count* indicates the relative part count of the mechanism where "baseline" is when the product has as many parts as the number of facets and creases in the paper origami model. If an approach is *conducive to sheet stock*, then materials in sheet form, such as sheet metals, can be easily used for the panels. The *second panel process* column lists any process in addition to a simple 2-D stock cutting process that is necessary to fabricate the panels. *Minimum number of processes* indicates the fewest number of distinct processes, including assembly, required to manufacture a mechanism using the given approach.

| Technique panel approach | Schematic representation | Part count | Conducive to sheet stock | Second panel process | Minimum number of processes |
|---|---|---|---|---|---|
| Tapered Panels | | | | | |
| monolithic |  | Baseline | No | Material removal | 3 |
| layered |  | High | Yes | Assembly | 2 |
| bent |  | Baseline | Yes | Bending | 3 |
| Hinge Shift | | | | | |
| monolithic |  | Baseline | No | Material removal | 3 |
| layered |  | High/Very High | Yes | Assembly | 2 |
| bent |  | Baseline | Yes | Bending | 3 |

and hybridized for specific products. The approach of using a thick membrane that was employed in the design of the ballistic barrier can also be applied for other systems where use of flexible layers for the joints between panels is desired. From the example of using sheet metal panels in origami-adapted mechanisms (Sec. 2.3), there are lessons in how to address shapes and thicknesses of panels, but not hinges.

In both the ballistic barrier and sheet metal panels examples, there are such lessons as that the hinges/joints of an origami-adapted mechanism matter and can have a significant effect on the mechanism as a whole as well as the lesson that integration of the panels and hinges is a vital part of the design that must be considered. In the example of the ballistic barrier, the requirement that the joints also have adequate ballistic protection governed the design to result in a different technique to accommodate thickness. In the sheet metal panels example, the hinges posed challenges because of the tight assembly tolerances required to avoid binding of the joints in both of the overconstrained mechanisms. To mitigate those tolerancing issues, the lesson from the ballistic barrier example of customizing and hybridizing the techniques and fabrication approaches to suit the design-specific needs could be applied.

Another key lesson that can be seen from more than one of the examples is that a more broad system approach is useful in examining how each aspect of a design affects its manufacturability. Things that may not initially be seen as impacting manufacturability, such as the origami pattern used for the ballistic barrier, may indeed have significant affects. Continually considering how design decisions will affect the product's manufacturability throughout the design process and making adjustments accordingly will help to improve the product's manufacturability and robustness.

## 4 CONCLUSION

Improving the manufacturability of deployable origami-adapted products is key to improving their robustness. This paper has examined some ways in which manufacturability can be considered in the design of deployable origami-adapted products by reviewing examples and highlighting lessons related to manufacturability from these examples. These lessons included customizing the thickness-accommodation technique and fabrication approach for the specific product, using a holistic approach to improve manufacturability by considering how each design decision impacts manufacturability, and the interfaces between joints and panels are essential to proper functionality of a deployable origami-adapted mechanism.

Future work that remains to be done includes developing

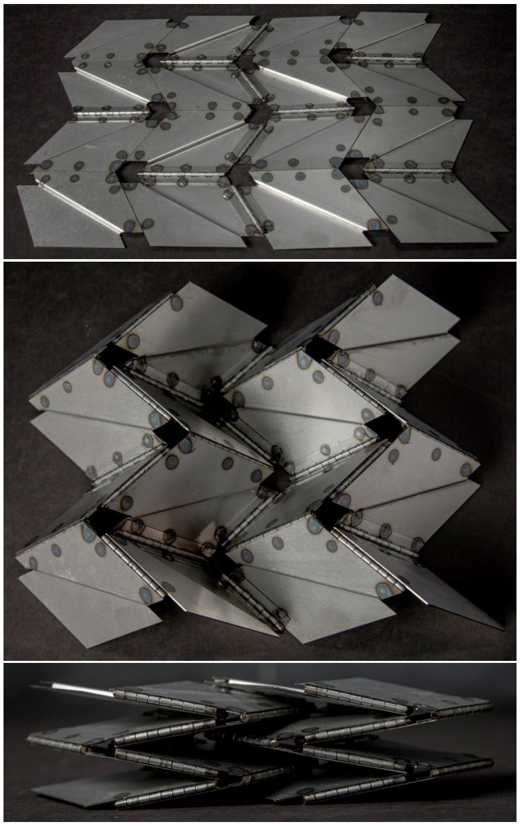


**FIGURE 8**: Sheet metal Miura-ori mechanism designed using the tapered panel technique shown unfolded, partially folded, and fully folded

guidelines for considering and improving manufacturability of deployable origami-adapted mechanisms as well as examining options for panel-joint interfaces. As work to address manufacturability of these mechanisms progresses and their robustness improves, better deployable origami-adapted mechanisms will be developed that will enable new accomplishments in many fields, including aerospace.

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