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An Approach for Designing Origami-Adapted Products with Aerospace Mechanism Examples

Jessica Morgan
Brigham Young University - Provo

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with Aerospace Mechanism Examples

Jessica Morgan

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Spencer P. Magleby, Chair
Larry L. Howell
Brian D. Jensen

Department of Mechanical Engineering

Brigham Young University

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ABSTRACT

An Approach for Designing Origami-Adapted Products
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Jessica Morgan
Department of Mechanical Engineering, BYU
Master of Science

The objective of this research is to develop a design process for origami-adapted products and demonstrate it using aerospace mechanism examples. Origami-adapted design is a type of origami-based design. Origami-based design ranges from abstract to concrete applications of origami to design and includes: origami-inspired design, origami-adapted design, and origami-applied design. Origami-adapted design adapts origami fold patterns into products while preserving functionality. Some of the desirable attributes of origami that are sought after in design include: 1) reduced number of parts, 2) stowability, 3) deployability, 4) transportability, 5) manufacturability from a flat sheet of material, 6) ease of miniaturization, 7) a single manufacturing technique (folding) and 8) low material volume and mass.

The proposed origami-adapted design process has four steps: define the problem, identify an origami solution, modify the fold pattern, and integrate. Intermediate steps apply tools to analyze and modify the origami fold pattern according to the design requirements. The first step defines whether origami is a viable solution by evaluating a set of starting criteria. Once it has been determined that origami is a viable solution, the design process guides the designer through a series of steps that modify the origami crease pattern until the final design is reached.

The origami-adapted design process is applied to the design of three aerospace mechanism examples: an origami bellows, an expandable habitat, and a deployable parabolic antenna. The design process is followed throughout the design of these aerospace mechanisms. The origami bellows is designed and tested as a highly compressible origami bellows for harsh environments. It can be designed to endure 100,000+ cycles in fatigue and underwent testing for thermal cycling, abrasion, and radiation. The second example is a proof-of-concept expandable habitat for implementation as a module on the International Space Station. The design process aides in selecting an origami crease pattern and modifying it for thick, rigid materials. The last example is a deployable parabolic antenna. It is based on the flasher fold pattern with a wedge of the pattern removed to create curvature. It is experimentally verified to be approximately parabolic.

The examples are shown to follow the origami-adapted design process and that the design process is flexible to accommodate a design's needs.

Keywords: design process, origami-adapted design, origami, parabolic antenna, bellows, origami classification

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NOMENCLATURE

D	Outer diameter
d	Inner Diameter
L	Stroke Length
L_c	Compacted length
L_d	Deployed length
a	Tessellation unit side length
b	Tessellation unit side length
c	Tessellation unit side length
c_0	Tessellation unit side length when $\delta = 0$
ϕ	Tessellation unit construction angle
δ	Deployment angle
δ_{max}	Maximum deployment angle
n	Number of tessellated sides
s	Number of stories or layers
ε	Strain
w	Dimensionless strain energy
H	Total deployment height

CHAPTER 1. INTRODUCTION

The primary objective of this research is to develop a preliminary design process for origami-adapted products and demonstrate its usefulness with examples. Origami uses folding to change a single flat sheet of paper into thousands of different shapes without using any cuts or adhesive. Origami has been applied to a variety of disciplines including the fields of engineering, mathematics and science [6]. In recent years, origami has influenced the design of several engineering projects to incorporate folding-based designs, such as a medical stent [7], deployable solar panel array [8,9], and automobile crash boxes [10]. Origami-based design has the potential to convert the aspects of origami into the realm of engineering. Some of the advantages of origami-based design are 1) reducing the number of parts, 2) stowability, 3) deployability, 4) transportability, 5) manufacturability from a flat sheet of material, 6) ease of miniaturization, 7) a single manufacturing technique (folding) [1] and 8) low material volume and mass.

Origami-adapted design is one of three types of origami-based design, which is a design inspired by the crease pattern, folding mechanism, or geometry of origami. Origami-adapted design seeks to preserve the desirable attributes of origami while modifying the origami model to meet design requirements such as rigid-foldability, material thickness, and hinge type. The advantageous attributes of origami, if accurately incorporated into a product, have the potential to change product design for space exploration, medical devices, camping gear, and the automotive industry. The origami-adapted design process will facilitate designers with limited knowledge and experience in exploring the potential applications of origami. This thesis will present the origami-adapted design process and demonstrate its implementation.

1.1 Document Organization

The remainder of this chapter will discuss preliminary work to develop a design process for origami-adapted products and the objectives of this research. Chapter 2 is a conference paper that classifies origami-based design and presents a preliminary origami-adapted design process. It waspresented at the ASME International Design Engineering Technical Conference in August 2015 and was published in the conference proceedings as DETC2015-47559. Chapter 3 summarizes the origami-adapted design process, reviews origami-based aerospace mechanisms, and presents aerospace mechanism examples for the origami-adapted design process. This chapter is a paper draft to be submitted for publication. Chapter 4 contains additional details about the design example and testing of a highly compressible origami bellows. It will likely be submitted for a future conference. Chapter 5 contains a summary and conclusions of the work presented in this thesis and recommendations for future work.

1.2 Background

This work builds on the work done by Kevin Francis who presents four considerations for origami-based design [1]. The Francis' four considerations include: rigid-foldability, crease characterization, material properties and dimensions, and manufacturing. This included suggestions for materials and manufacturing methods for origami-based design. This is an initial attempt to identify the elements of origami-based design and contributes to the current development of a preliminary origami-adapted design process.

Researchers have developed tools to address certain origami design problems, including: rigid-foldability [11], thickness accommodation [8], hinge selection [12], actuation methods [13], and manufacturing methods [7]. These tools are supplemental to the design process.

There is a history of applications of origami to product design but no method to describe this process. The kinematics of origami have lead to its implementation to deployable structures in both aerospace and architectural industries [8, 9, 14]. The deployability of origami also has implications in other industries such as: sporting goods, home decor and appliances. Origami is also a source of inspiration to simplify manufacturing methods using tessellations or patterns [7]. Even static formations of origami have been applied to areas of architectural structures and energy absorption [10, 15]. Researcher are to discover new applications of origami to engineering.

Origami design is a complex process with lots of design considerations. The origami-adapted design process makes applying origami to design more approachable and deeps the understanding of the complex process and considerations involved in origami-adapted design.

1.3 Objectives

As stated the objective of this research is to develop a design process for origami-adapted design. This objective can be broken up into intermediate goals, which are:

- Classify the types of origami-based design
- Identify available tools for the design process
- Develop a preliminary design process for origami-adapted products
- Apply the design process to create desirable origami-adapted products.

The classification of origami-based design clarifies the extent of origami-adapted design and helps to determine pre-existing origami-adapted products that can be used as examples. The origami-adapted design process utilizes tools and knowledge previously developed to analyze origami. The design process is based on pre-established design processes and uses biomimetic design process as a model. The origami-adapted design process is applied to three examples that develop origami-adapted aerospace mechanisms.

CHAPTER 2. A PRELIMINARY PROCESS FOR ORIGAMI-ADAPTED DESIGN

2.1 Introduction

Origami, the ancient Japanese art of paper folding, uses folding to transform a single flat sheet of paper into one of thousands of different shapes without using any cuts or glue. Origami has existed for thousands of years as an art form, but recently the scientific field has developed an increased interest in the art. Origami practices and principles have been applied to a variety of disciplines including engineering, mathematics and science [6]. In recent years, origami has influenced the outcomes of several engineering products to incorporate folding-based designs, such as a medical stent [7], deployable solar panel array [8,9], automobile crash boxes [10], and medical products [1,4]. Origami-based design has the potential to convert the characteristics of origami into the realm of engineering. Some of the possible advantages that result from origami-based design are 1) part number reduction, 2) stowability, portability, and deployability, 3) manufacturability of mechanisms and structures from a flat sheet of material, 4) a single manufacturing technique (folding), 5) reduced assembly, 6) ease of miniaturization, 7) controlled mechanism failure, and 8) low material volume and mass [16].

Origami-based design aspires to transform the characteristics of an origami paper model into a usable product. Origami-based design can result in a spectrum of products, ranging from the abstract to concrete applications of origami in the design. The design approach should adapt depending on the desired fidelity of the product to the basic origami principles of folding a monolithic sheet of paper. Origami-based design can be broken down into three different design classifications: origami-inspired, origami-adapted, and origami-applied which range from abstract to direct applications of origami, respectively. Origami-adapted design adapts products based on origami away from a direct application while maintaining functionality. Origami-adapted design broadens the applications of origami that are able to take advantage of origami's desirable attributes, which is why it is the focus of this research.

Design tools for origami-adapted products are spread out across dozens of resources. Currently, there is no method, process or literature that ties all of the pieces of origami-adapted design knowledge together into one accessible source. There exists one initial exploration of an approach to origami-adapted design, which consists of a list of four main design considerations and methods of application but this list remains incomprehensive [16]. The objective of this research is to build upon the previous work to develop a preliminary process for origami-adapted design, thus improving the ability of engineers to reliably develop origami-adapted products.

2.2 Background

Significant research has been done to further the understanding of origami and how it applies to other fields. This research covers a wide variety of disciplines, such as mathematics, science, education, manufacturing, and design. Origami research related to engineering design can be grouped into three different areas: modeling origami, engineering parallels, and engineering applications, all of which lay the foundation for a design process for origami-adapted products.

2.2.1 Modeling Origami

Origami can be modeled using mathematical analysis. Mathematicians were some of the first in the research community to develop an interest in origami [6]. Demaine and O'Rourke have developed a number of theorems exploring the possibilities and limitations of origami, including solving origami folding problems [6]. The mathematical principles explaining origami in such papers are a valuable reference for engineers in modeling and understanding origami.

Mathematical modeling is used as the basis for many origami-based design considerations such as rigid foldability, thick origami, and defining kinematic motion (which shall be addressed later in this work [4, 14]). Articles that describe origami and its relative motion are useful for modeling and designing origami-adapted products [17].

2.2.2 Engineering Parallels

The second research area of interest is identifying parallels between origami characteristics and the traditional modeling performed to understand engineering disciplines. Origami can be

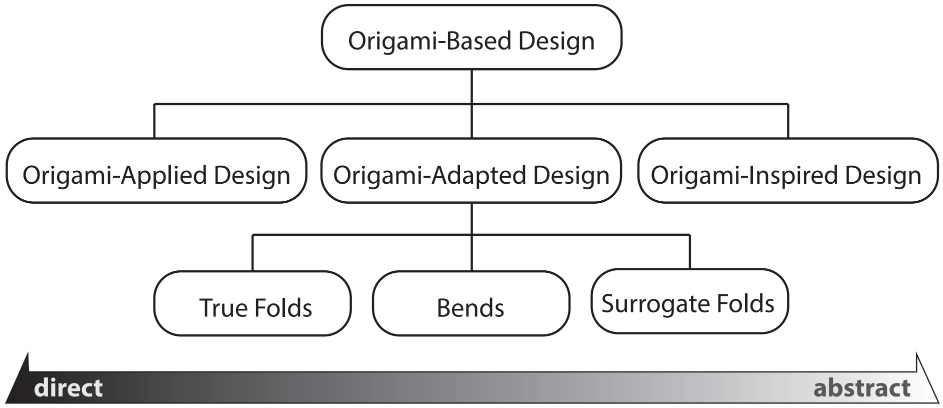

Figure 2.1: The original classification of Francis [1] of origami-based design into origami-adapted and origami-inspired design.

classified as a compliant mechanism, specifically as a lamina emergent mechanisms (LEM), since it is fabricated from a planar material and any resulting motion emerges from the plane of fabrication [18]. Comparing origami to LEMs opens up new possibilities in origami design [19].

Another parallel between origami and an engineering discipline is that of spherical mechanisms, where a single panel in origami corresponds with a kinematic link and creases are considered joints [18, 20]. Spherical mechanisms embedded into the crease pattern are the origin of motion in action origami, origami that has motion when folded into its final state.

Both LEMS and spherical mechanisms can be used to model, classify and explore new possibilities for origami-based design [21].

2.2.3 Engineering Applications and Processes

The third research area of interest is that of engineering applications. Using origami in engineering has driven developments and research in origami-adapted design. The field of engineering has used origami for geometry, pattern generation, material strength, kinematics and more for product design and analysis [7].

There are a wide variety of examples of origami applications in engineering. One application of origami to engineering design is using its kinematics to make deployable structures. This has opened new doors in the realm of deployable structures in the aerospace and architectural industries, which in turn has furthered the development of origami-adapted design [8, 9, 14]. The

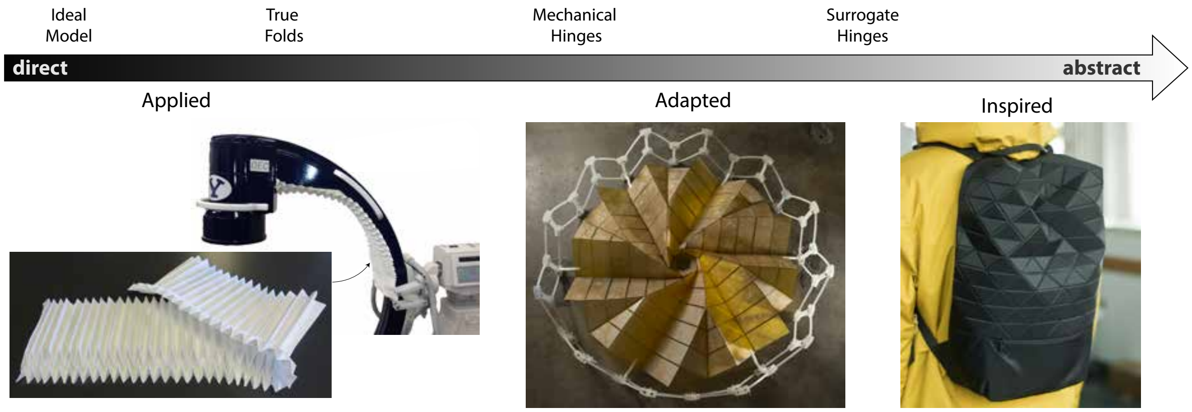

Figure 2.2: The fidelity continuum for origami-based design, ranging from origami's ideal mathematical model to abstract applications.

deployability of origami also has implications in other industries such as: sporting goods, home decor and appliances. Other applications of origami are using origami tessellations or patterns to simplify the manufacturing process of pleated fabrics [7]. Origami has also been used in architectural design to determine the curvature of a surface [7]. Origami has also been used for applications of energy absorption [10, 15]. Research in origami is continuing to discover new applications of origami to engineering.

In summary, the aforementioned research in origami on modeling origami, engineering parallels and engineering applications and processes lay the foundation for origami-adapted design. These research topics independently address some of the challenges present in origami and possible tools for overcoming these challenges during the design process.

2.3 Classification

Origami-based design ranges from abstract to concrete applications of origami which can be separated into different classifications. This work refines the previous origami-based design classification done by Francis et. al., shown in Figure 2.1, by adding another level of classification of origami-based design called origami-applied [1]. The subsets of origami-based product design are origami-inspired design, origami-adapted design, and origami-applied design.

Figure 2.1 demonstrates how origami-based design can be broken into three different classifications. These classifications are determined based on how directly origami is applied in the

Characteristic	References	Definition	Application
Evaluation and Iteration	Dym, Eder, Haik, Mattson, Niebel, Pahl, Stoll, Ulrich	Evaluations determine if the design meets the design requirements and whether iteration is necessary to improve the design.	The complex tradeoffs in origami-adapted design require frequent evaluations and iteration during the design process.
Linear Design	Ciambrone	Design without iteration.	This is quicker and simpler but impractical for origami-adapted design.
Clear, Concise Diagram	Dym, Pahl, Ulrich	Diagrams are used to outline and explain design processes and frameworks.	A diagram will facilitate the explanation for the framework for origami-adapted design.
Enterprise Structure	Eder, Ulrich	The design within enterprises which incorporates multiple layers.	This is beyond the scope of a framework for origami-adapted design.
Design for X	Ciambrone, Ulrich	Design for X is designing for manufacturability, cost, environment or another design goal.	Origami-adapted design is too diverse for a focused design goal but this can be included in individual projects.
Generalized	Dym, Eder, Haik, Mattson, Neibel, Pahl	A design process applies to any product and is simple to adapt.	Origami-adapted design focuses on the design of a specific type of product.
Transferable	Ciambrone, Dym, Haik, Mattson, Niebel, Pahl, Stoll, Ulrich	The design is sufficiently well-documented to be recreated without reengineering.	This is important for all design projects but ultimately depends solely on the designer.

Figure 2.3: Results from a study of design processes showing design process characteristics, their definition and potential application to origami-adapted design.

design. The classifications fall along a fidelity continuum, which is shown in Figure 2.2. The continuum starts, on the left, with the ideal origami model and becomes increasingly abstract. The ideal model is an origami model that assumes zero thickness which is the basis for all simplified origami models. Figure 2.2 also shows examples of different origami-based products that fall into each of the named classifications. These classifications will be explained in further detail below.

Origami-applied design is cases where origami fold patterns can be directly applied to a product's design. These have a direct correlation between origami and the emergent product. Figure 2.2 shows the C-arm shroud as an example of origami-applied design. The C-arm is a medical imaging device where a shroud is necessary in order to maintain sanitary conditions. The shroud is a combination of the v-fold and Miura-ori fold patterns in a material with similar properties to paper. This product required minimal adaptation of the original origami fold patterns and has a direct correlation between origami and the emergent product. Another example is origami crane earrings, which is a direct application of origami to product design.

Origami-adapted design adapts origami fold patterns into products while maintaining functionality. These products move away from the ideal origami model and are more abstract. The deployable solar panel array is an example of an origami-adapted design, shown in Figure 2.2 [8]. This product stems from the origami fold pattern called the flasher; the fold pattern had to be adapted to accommodate for the thickness and rigidity of the material. Another example of an origami-adapted design is a deformable robot wheel that is based on the magic-ball fold pattern [22]. The initial design of the product required little adaptation from the original origami fold pattern but as the product developed it adapted further from the ideal origami model. The wheel is constructed of rigid PVC segments adhered to and sandwiched between two layers of fabric, which resulted in adaptation away from the original origami fold pattern. Other examples of origami-adapted design include rigid core panels used in zeta cores and honeycomb structures.

Origami-inspired design is any product that is inspired from origami which has a loose link between the emergent design and origami, including designs that simply remind one of origami through means such as geometric patterns and folding kinematics [1]. Origami-inspired design is a much broader topic with examples like static architectural structures [7], an origami microscope [23], and home decor.

Origami-applied, origami-adapted and origami-inspired design fall along the continuum according to their degree of abstraction from the ideal model. Making adaptations to an origami-based design has the potential to vary the design's position along the fidelity continuum and its design classification. For example, adjusting the crease type from true folds to surrogate hinges, as indicated in the diagram, will shift the design's position along the continuum and change its classification. True folds are the closest to the ideal model while replacing the creases with mechanical or surrogate hinges steps the design away from the ideal model.

At one extreme of the continuum, the abstract approach of origami-inspired design risks the loss of potential advantages and functionality of origami that are sought after in engineering design. Whereas, origami-applied design maintains functionality but is limited to thin paper-like materials and thus has limitations in its applications. Origami-adapted design bridges the gap between origami-applied and origami-inspired design by adapting from the ideal origami model to accommodate specific application needs while maintaining the desired functionality for which origami was choosen.

Adapting origami while maintaining functionality presents several design challenges which introduces the need for a process for understanding origami-adapted products to facilitate designers in addressing these challenges.

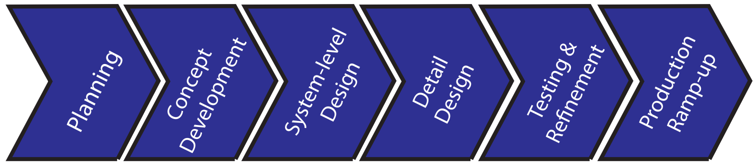

Figure 2.4: Schematic of a general design process based on the design processes considered in this study.

2.4 Preliminary Process Development

The design process for origami-adapted products is founded on basic design process principles which are determined through a study of selected design processes. The developed design process originated with a general design process and matured using characteristics from various design sources. The steps of a general design process, as seen in Figure 2.4, are: 1) planning 2) concept development, 3) system-level design, 4) detail design, 5) testing and refinement, and 6) production ramp-up [24, 25]. Selected design processes were studied for process characteristics beyond the general process and evaluated for their potential application in the preliminary process for origami-adapted design.

2.4.1 Design Process Characteristics

Nine different design processes were evaluated to extract elements that could be useful in an origami-adapted process. The nine design processes studied are that of Ciambrone [26], Dym et al. [27], Eder and Hosnedl [28], Haik [29], Mattson and Sorensen [25], Niebel and Draper [30], Pahl and Beitz [31], Stoll [32], and Ulrich and Eppinger [24]. Figure 2.3 presents characteristics that emerged from the study, including: iteration and evaluation, linear design, clear and concise diagram, enterprise structure, design for X, generalization, and transferability. Figure 2.3 also discusses each characteristic's potential application to the preliminary design process.

Characteristics like linear design, enterprise design, design for X, generalization, and transferability are beyond the scope for a general understanding of a design process for origami-adapted products. Origami-adapted design requires multiple trade-offs and interdependencies that can't be addressed in linear design with no iteration. Enterprise design and design for X add layers of complexity to design processes that are useful for enterprises and for achieving specific design outcomes. These design elements are not beneficial for a general understanding of a specific type of product's design process.

Generalization refers to a general design process which applies to the design of any product. This is a good starting point for an origami-adapted design but would not provide a deeper understanding to the design of this specific type of product. A design process for stimulating the understanding of origami-adapted design needs to be specific to origami products. Transferability of the design will be left to the designer as it is beyond the scope of this discussion.

Design characteristics that are useful for understanding a preliminary design process for origami-adapted products are evaluations and iteration and a clear, concise diagram. The complex interdependencies and trade-offs of origami-adapted design make iteration a key element of the design process. Evaluations comparing the product to the requirements drive iterations and further improve the design. A clear and concise diagram is key for assisting designers in understanding the overall process of origami-adapted design.

This study of design processes reveals the key characteristics of design process that are helpful in understanding the design process for origami-adapted products.

2.4.2 Biomimetic Design Parallel

A parallel to origami-adapted design is that of biomimetic design, or bioinspired design. Bioinspired design is design based on biological solutions. Helms developed and validated a six step design process for bioinspired design. Helms validated the process with multiple case studies. The steps are: 1) problem definition, 2) reframe the problem, 3) biological solution search, 4) define the biological solution, 5) principle extraction, and 6) principle application [33, 34]. These steps address the concept development, system-level design and detail design steps of the general design process, shown in Figure 2.4, as they apply this specific based design process. The challenge of design based on a specific source is finding an appropriate solution, extracting the information and applying it [33, 35, 36]. The bioinspired design process is a tested design process that acts as a reference for understanding the origami-adapted design process.

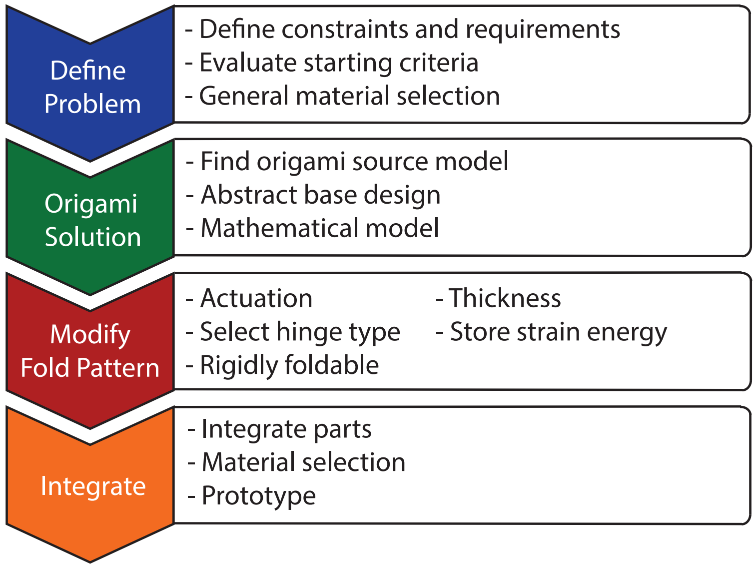

Figure 2.5: Preliminary Process for Origami-Adapted Design. The arrows and overlap between steps indicate iteration.

2.5 Preliminary Process for Origami-Adapted Design

Observations from the study of design processes, the parallel biomimetic design process, and completed origami-adapted products developed into a four step design process for origami-adapted design. Figure 2.5 is a diagram describing the origami-adapted design process developed which emphasizes in the concept development, system-level design, and detail design phases of the general design process. The planning, testing and refinement, and production ramp-up phases that are included in the general design process are similar for origami-adapted products as they are for other products and thus not included. In the diagram, the arrows and overlap between phases relate that there is overlap and iteration between each step. An overview of this preliminary process for origami-adapted design will be discussed in the proceeding sections.

2.5.1 Define Problem

A critical element to understanding origami-adapted design is identifying the situations in which it is applicable and foreseeing the outcomes. Based on observation, the origami-adapted design process starts, like all design processes, with defining the problem to be solved. This

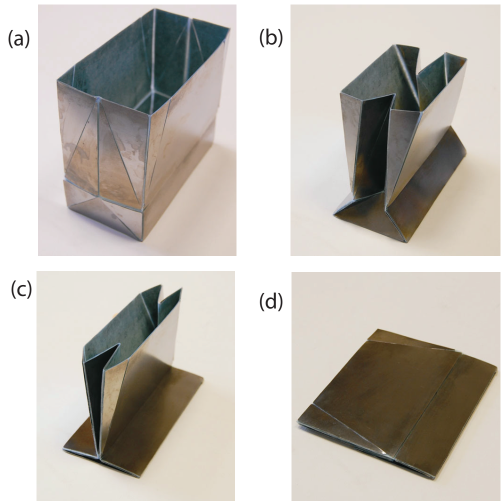

Figure 2.6: A folding rigid tall shopping bag designed by Wu and You [2].

includes establishing the constraints and requirements for the product, evaluating whether or not the product meets the criteria for origami-adapted product design and determining a material type.

Constraints and Requirements

All design projects should start with clearly defining the problem by determining the constraints and requirements. Constraints and requirements that correlate with origami-adapted products are that the product needs to be compactable, transportable, stowable, fold flat, economic, sheet manufacturing, rigid material, kinematic, static, continuous material, material type, specific force profile, mechanical output, precision of motion, etc.

Evaluate Starting Critieria

Origami product design is not a viable solution for all products; products should meet a set criteria before proceeding forward with origami-adapted design. The product should be evaluated according to these three criteria:

1. The product utilizes sheet like material
2. The product has two distinct configurations
3. The product disfavors cutting and gluing (monolithic)

If the product requirements meet these criteria than origami-adapted design solutions may be viable and attractive. If the product meets some but not all three of the criteria, origami may or may not be a viable solution. If the product does not meet any of the criteria than origami may not a viable solution and other solutions should be sought.

An example of a viable origami-adapted product is a folding rigid, tall shopping bag designed by Wu and You as shown in Figure 2.6 [2]. Figure 2.6 shows the shopping bag in different folded states. The shopping bag is innovative in that it is the first collapsible tall, rigid shopping bag, given that most shopping bags are manufactured from non-rigid material. The design of the shopping bag passes all three of the starting criteria. It is made out of a sheet like material. It has two distinct configurations in both its open and closed positions. The shopping bag is made out of hylite, aluminum sheets bonded to a polypropylene core, which makes it possible to manufacture the bag from a monolithic material and cutting and gluing is not necessary.

These three design criteria are a guideline to determine whether origami-adapted design is a viable and attractive solution.

Not all previously designed origami-adapted products meet these three design criteria. Failure to meet one or more of the design criteria does not indicate that origami-adapted design is not a possible solution. In this situation, origami-adapted design may still be possible, but the viability and fit of the solution are put into question. Whereas, satisfying the criteria does indicate that origami design is a good solution.

General Material Selection

There are several design options for the general material of an origami-adapted product; these depend on whether the material needs to be flexible, rigid, a hybrid of the two or have multiple flexible layers. Origami is primarily constructed out of paper which is a flexible material that allows flexing in the panels while folding. Special considerations must be made in order to do origami in a rigid material, thus it is advantageous to foresee the material and design options early on in product development since it affects the remainder of the design.

Two considerations in selecting the general material are the rigidity and continuity requirements of the product. Rigidity refers to the stiffness of the material and has no allowance for deformation in the panels. Continuity refers to a closed surface without any perforations or interruptions. These two design considerations combine to result in four different general material design options. These four different general material design options are shown in Figure 2.7, which gives prospective as to the possible design options for origami-adapted design. Figure 2.7 includes the material design options, an explanation and example of each option and how to make a selection depending on the continuity and rigidity requirements of the product.

The four general material design options are rigid, flexible, multiple flexible layers and hybrid. Figure 2.7 shows how these two considerations influence the general material selection. For products that need to be rigid and continuous this results in a hybrid material. A hybrid material has rigid panels with a flexible membrane. If a rigid material needs to be cut to allow folding, continuity is maintained with the adhesion of a flexible membrane or a flexible material solely at the creases. For products that need to be rigid and interrupted (non-continuous) this results a rigid material that can have cuts or slits. Products that need to be flexible and continuous have the option of either a single continuous flexible material or multiple layers of flexible material. The need for multiple layers will not be fully determined until the selection of the final material and crease design. Some flexible materials are prone to areas of stress concentration along the folds and vertices for which holes or slits can be cut as stress relievers. In this case adhering a second layer of flexible material will maintain continuity. For products that need to be flexible and interrupted this results in a flexible material that can have cuts or slits.

Figure 2.7 has examples of products that demonstrate the need for different general material design options, such as the tall rigid shopping bag, heart stent, orikaso camping plates, and oriceps.

The tall rigid shopping bag's project requirements included that the bag protect the contents of the bag, be rigid and tall. This translates in that the bag needs to be rigid and continuous so it is made out of a hybrid sheet material [2]. The heart stent requires rigidity to provide structural stability to the artery but does not need to be continuous [37]. The heart stent is designed out of a single rigid material with holes in the vertices to prevent stress concentration. As for the orikaso foldable backpacking dishes, they need to maintain continuity to hold the liquid and food without spilling but does not need to be completely rigid. The orikaso is made out of a flexible plastic with living hinges along the crease lines and is an example of a flexible, continuous material using a single flexible material. Currently, there are no known examples of multiple flexible layers but it is a design option for continuous, flexible products. The oriceps needs to be able to grasp fragile organs but does not need to completely enclose the object thus a flexible, interrupted material satisfies the design requirements [4]. The oriceps are made out of polypropylene with slits to create hinges and allow flexing.

Product constraints and requirements determine the general material from the four design options. This provides foresight throughout the remainder of the design process.

This concludes the problem definition phase for origami-adapted design. At this point the product requirements are known, origami is determined to be a viable design solution and the general material is selected to be a flexible, rigid, hybrid or multiple flexible materials. At this point the problem is properly defined and an origami solution can be sought.

2.5.2 Origami Solution

This step involves finding an origami solution to the design problem. This includes finding the origami source model, extracting the base design and creating a mathematical model.

Origami-adapted design is based on origami crease patterns. One of the challenges to developing origami-adapted products is finding a useful origami source model. The origami source model is the initial crease pattern from which stems the final product. Origami crease patterns are chosen for a product based on their geometry and function. Currently, most origami source models are selected based on experience and intuition but can also be found by searching journal articles, origami books and online forums.

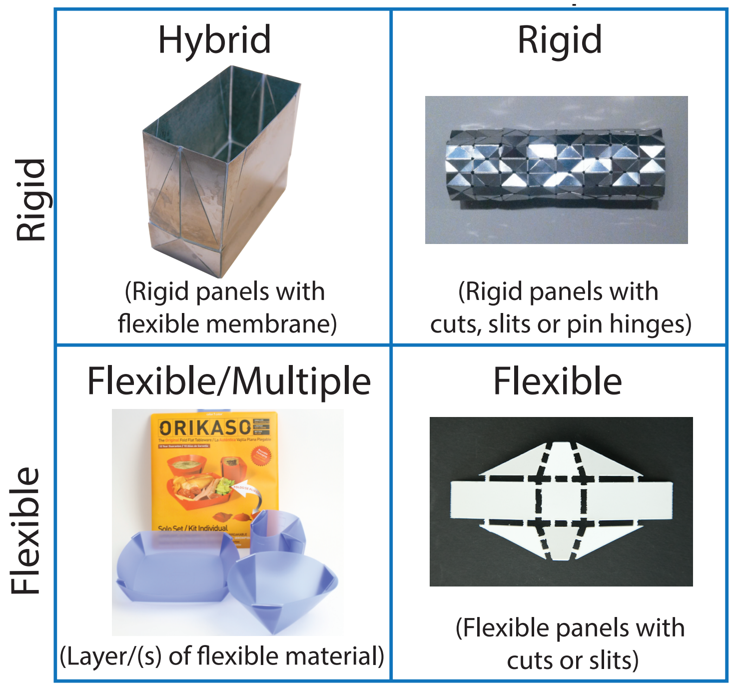

Figure 2.7: A diagram showing the general material design options based on whether the product needs to be rigid and/or continuous and classifies example products such as the tall rigid shopping bag [2], heart stent [3], orikaso and the oriceps [4].

The origami crease patterns most frequently applied to products are the flasher, water bomb tessellations and Miura-ori patterns. Examples of products with a strong correlation to their origami source model are the deployable solar array based on the flasher [8], the deformable-wheeled robot from the magic eight ball [22], the Oriceps from the chomper [4], and a resonant chamber from the triangulated water bomb tessellation [38].

Frequently, origami source models have additional creases and material that are not necessary and would hinder the product's function. Abstracting the base design is eliminating these excessive features in the crease pattern until only the creases and material that are key to the function remain. Abstracting the base design includes: removing excess material and creases, adding creases, making cuts and rearranging features. The end result is a simplified origami source model.

Figure 2.8 shows the Oriceps, a surgical grasper, and its origami source model the chomper. The chomper crease pattern is excessive for the design of a simple grasper, so features unnecessary to the function were eliminated, including material and creases, and adding features to improve the function, such as additional creases, resulting in the Oriceps crease pattern as shown.

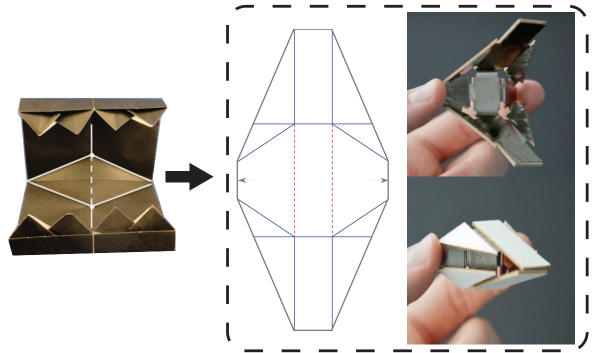

Figure 2.8: The chomper, on the left, is the origami source model for the Oriceps. The crease pattern was modified to abstract the base design to achieve the grasping function [4].

Some origami-adapted products require specific kinematics and geometry for their function so a mathematical model is useful to achieve either the desired precision, illustrate the motion, or quick estimation of performance. Mathematical models of origami have been used to analyze kinematics, energy absorption, mechanical advantage, geometry, and manufacturing process. For example, mathematical models were used in the design of origami crash boxes [10] and airbags [39] to better understand their motion.

2.5.3 Modify Fold Pattern

At this point in origami-adapted design the problem is defined and a simplified origami solution found. The proceeding step in origami-adapted design further modifies the crease pattern away from traditional origami as product needs are taken into account. This part of origami-adapted design is highly coupled between the different design considerations and requires iteration. Some design considerations that modify the crease pattern are: actuation method, utilizing strain energy, hinge type, rigid foldability, and thickness.

Actuation Method

Actuation of origami-adapted products requires different considerations than for non-actuated products. Wilcox presents the steps and considerations of including actuation in the design of origami-inspired mechanisms [13].

Utilizing Strain Energy Storage

Utilizing strain energy is using the strain energy that is stored in the creases and non-rigid panels of origami to improve the function of the origami-adapted product. The material and crease type are the main factors in strain energy storage. The hinge index is a measure of a material's ability to store strain energy [16]. Alterations to the creases like perforations, deep scoring, and cycling decrease the strain energy storage which needs to be taken into consideration when designing the product's hinges.

Select Hinge Type

Possible hinges that can be used in origami-adapted design are: creases, traditional hinges, surrogate hinges or hybrid materials. Three of these methods (creases, traditional hinges and surrogate hinges, respectively) are shown in Figure 2.9 applied to a water bomb base. Folding paper creates creases that are capable of 360° rotation and have a long fatigue life which is difficult to duplicate in non-paper materials. Creases are possible in paper-like materials or by thinning and/or perforating a thick material. Origami folds can also be replaced by traditional hinges which have a similar motion, but increases the assembly process. Another design option is surrogate hinges which are compliant mechanisms that can be implemented in thick, rigid materials to mimic bending with minimal parasitic motion [5]. Another option is to use a hybrid material where a flexible material replaces the creases and has a rigid material for the panels which is a material design option for rigid, continuous products.

Rigid Foldablility

A rigidly foldable crease pattern is an origami fold pattern that can move through its full range of motion without deformation in the panels or self-intersection. If the design uses a flexible material or is static then rigid foldability may not be a concern. For any kinematic, rigid design, the crease pattern needs to be modified for rigid foldability. The tall, rigid shopping bag is an example of a crease pattern modified for rigid foldability. It is not always possible to adjust a crease pattern to be rigidly foldable and this requirement needs be taken into account when selecting an origami source model. Certain creases patterns, such as the Miuri-ori crease pattern, are known to be rigidly

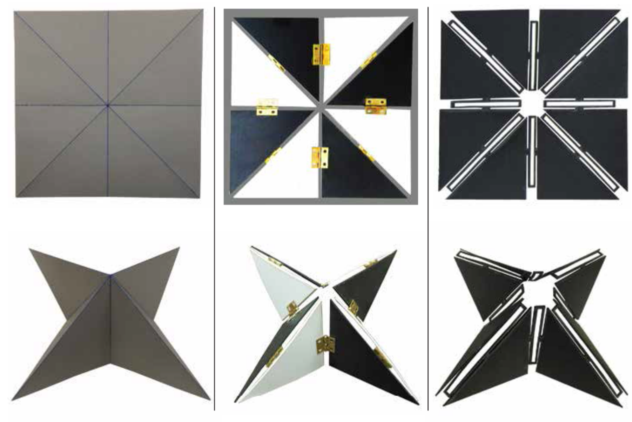

Figure 2.9: Three different types of hinges applied to a water bomb base: true fold, traditional hinge and compliant surrogate hinge.

foldable crease patterns and are used often for this reason. Rigid materials also coincide with thick materials which requires further modification to the crease pattern.

Accommodating Thickness

The ideal mathematical origami model assumes a zero thickness material. This assumption is a good approximation for origami paper when applied to crease patterns that do not involve extensive layering. This approximation losses accuracy as the material thickens and with layering. Origami crease patterns are designed around the ideal mathematical model and do not take into account material thickness. Crease patterns have to be modified to accommodate for thickness. Product designs require multiple iterations to modify a crease pattern for both rigidity foldability and thickness especially since the actuation method, strain energy storage and hinge type also effect these design decisions.

The origami solar array, shown in Figure 2.10, has a crease pattern that is adjusted to accommodate rigid foldability and the thickness of the material [8]. The creases are made using a hybrid material with rigid solar panels and a flexible membrane. Strain energy storage is low and thus not a major concern since a thin, flexible material is used for the membrane. The solar array is actuated using the attached truss. It took several iterations to account for all the design considerations and converge to this design for the origami-adapted deployable solar array.

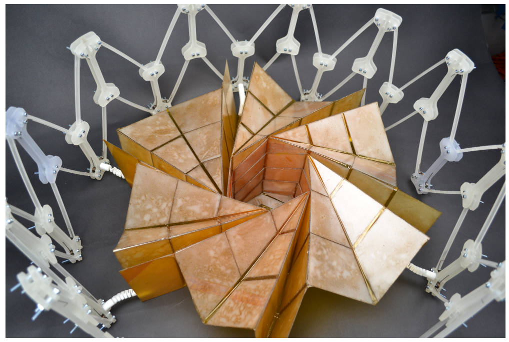

Figure 2.10: Origami-adapted solar array that modifies the crease pattern to accommodate thickness and rigid foldability.

2.5.4 Integrate

The final step in origami-adapted design is integrating the parts together, finalizing the material selection and prototyping the design. All of the previous design steps are integrated together into a complete design. If not previously determined, the material(s) are selected for the design. The product's materials depends on the general material options, the crease type, thickness constraints and the amount of desired strain energy storage. Prototypes are a useful tool for making design decisions and integrating all the design considerations together. Prototypes fall along a spectrum of fidelity starting with rough models and crease patterns and increasing in fidelity until a final product is created. Upon completion of a working prototype, this concludes the preliminary process for origami-adapted design. This can be followed, based on the general design process, with testing and refinement and production ramp-up for full-scale manufacturing.

2.6 Conclusions

The preliminary origami-adapted design process presented in this paper is meant to assist engineers and designers in understanding how a product steps from an origami paper model to an origami-adapted product. Origami-adapted design has four main steps: define problem, identify origami solution, modify the fold pattern, and integrate. This preliminary origami-adapted design process is based on the general design process, characteristics of design processes, bioinspired design and examples of previously designed origami-adapted products.

Origami-adapted products are difficult and complex to design but have several engineering design advantages. Origami-adapted design is desirable due to its potential to improve traditional engineering design using 1) part number reduction, 2) stowability and deployability, 3) manufacturability from a flat sheet of material, 4) a single manufacturing technique (folding), 5) reduced assembly, 6) ease of miniaturization, and 7) low material volume and mass [16]. These advantages are highly desirable in engineering making origami a potential game changer in engineering design and manufacturing.

Future work will build on and refine this preliminary process to create a more detailed flow of decisions and tools. Key to this refinement will be stronger guidelines for selecting the origami source model, and understanding the role of iteration relative to material selection, hinge type, rigid foldability and accommodating for thickness. With refining this process there will be broader opportunities to implement, validate, and improve the origami-adapted design process with practicing engineers and designers.

CHAPTER 3. AN APPROACH TO DESIGNING ORIGAMI-ADAPTED AEROSPACE MECHANISMS

3.1 Introduction

Origami folding methods have the ability to transform paper into unlimited numbers of shapes and patterns without any cuts or glue. Derivatives of this art expand its boundaries by exploring different materials, cuts, and use of adhesive. Engineering has taken an interest in origami and developing it further for applications. Characteristics of origami that are of interest to engineers include: 1) stowability, 2) portability, 3) deployability, 4) part number reduction, 5) manufacturability from a flat sheet of material, 6) a single manufacturing technique (folding), 7) reduced assembly, 8) ease of miniaturization, and 9) low material volume and mass [1].

These characteristics are of particular interest for aerospace engineering applications where stowability, portability, and deployability often drive a product's design. Origami has inspired the design of several aerospace products, including a deployable solar panel array [8, 9], an eyeglass telescope [40], and a Starshade [41]. It is anticipated that many more areospace mechanisms can utilize the potential benefits of an origami-based design.

The research presented in this paper has two main objectives: to demonstrate origami as a useful tool for aerospace mechanisms and provide examples to demonstrate an approach to designing origami-adapted products. Origami-adapted design is a complex process involving specialized tools. Understanding and employing an origami-adapted design process can facilitate future designs with the potential to greatly influence fields like aerospace mechanisms. This paper will proceed as follows: background information on origami-based products and the design process, and three aerospace mechanism examples to illustrate the design process.

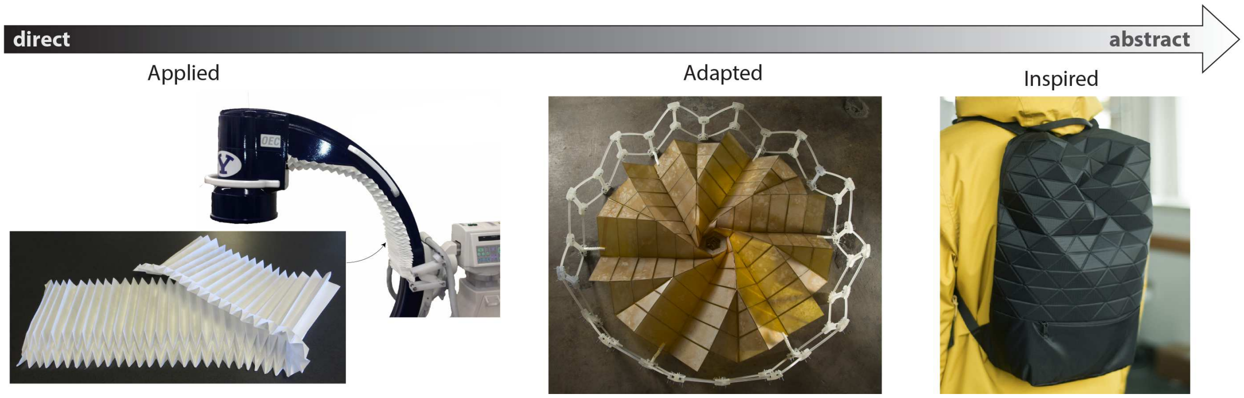

Figure 3.1: The fidelity continuum ranging from the ideal mathematical model of origami to abstract applications of origami.

3.2 Background

This research focuses on an approach to origami-adapted design which is a specific branch of design based on patterns and behaviors found in origami. This section presents a classification of origami-based products, introduces examples of origami-based design in the aerospace industry, and summarizes a basic origami-adapted design process that will be built upon in this paper.

3.2.1 Classification Summary

An origami-based design is a design that has a link to origami. Origami-based designs can be arranged on a fidelity continuum that can be divided into three regions: origami-applied, origami-adapted, and origami-inspired. These regions define classifications of origami-based design that fall along the fidelity continuum ranging from direct to abstract applications of origami to the design. Figure 3.1 demonstrates how each of these classification regions fall along the fidelity continuum with supporting examples [42].

Origami-applied design implies a direct application of origami to design requiring minimal or no adaptation. The C-arm shroud, shown in Fig. 3.1, is an example of an origami-applied design utilizing a combination of v-fold and Miura-ori fold patterns created with Tyvek, a paper-like polymer. The design of this mechanism involved identifying a fold pattern that met the requirements and applying it without any additional adjustments, which makes it a direct application of origami to product design.

Next along the fidelity continuum is origami-adapted design. Origami-adapted design transforms an origami design away from the base origami model to accommodate design requirements such as rigid-foldability, thickness, and non-crease-like hinges. The origami solar panel array, shown in Fig. 3.1, is adapted from the flasher origami crease pattern. The crease pattern had to be altered to accommodate the thick, rigid solar panels [8]. Depending on the degree of adaptation, an origami-adapted design can fall anywhere between origami-applied and origami-inspired classifications on the fidelity continuum.

Lastly, origami-inspired design yields designs that are inspired by origami but do not have a direct link to origami, utilizing only aspects of origami such as folding or geometric shapes. Figure 3.1 shows the Tessel backpack as an example of origami-inspired design [1]. The Tessel backpack was inspired by origami but does not have a direct connection to an origami pattern or manufacturing technique.

These three classifications: origami-applied, origami-adapted, and origami-inspired all fall in the continuum of origami-based design. This research focuses on origami-adapted design. While origami-adapted design holds great promise to produce innovative devices and products, it is also quite complex requiring specialized tools for modification of origami patterns.

3.2.2 Origami-Based Aerospace Mechanisms

Because origami is a type of compliant mechanism, it has similar advantages to complaint mechanisms in aerospace environments such as reduced weight, reduced friction and wear, elimination of lubricants, increased precision, and ease of miniaturization [43]. Combined with the characteristics of origami, these advantages are of particular design interest for deployable and stowable mechanisms. Origami has influenced several areas of space deployables including antennas, solar arrays, solar sails, and booms [8, 44, 45]. These products can fall anywhere along the origami-adapted design range in the fidelity continuum. Past origami-applied and adapted aerospace mechanisms have originated from a select few origami patterns such as the flasher, folding cylinders, and basic z and v folds [46].

The flasher fold pattern is often applied to spherical designs that fold up around a central hub and deploy out radially [47]. The flasher was used to design deployable spiral membranes for RF and transmissive diffractive optics [9]. Adaptations to the flasher pattern have made it applicable to thick, rigid designs such as the origami solar panel array and the optical blanket of the Starshade, a device to block out light pollution from other stars [8, 41].

Foldable cylindrical origami patterns have been used for stowing long cylinders or booms used for structure deployment and stabilization. An inflatable, rigidizable boom has been folded using simple z-folds along its length to make it stowable and easy to inflate [46, 48]. Other origami fold patterns such as the accordion (also known as the triangular fold pattern) or Kresling pattern collapse a cylinder along its length and can fit inside an annulus in both the deployed or stowed configuration. These fold patterns have been analyzed and recommended for space applications [49–51]. The Kresling fold pattern has specifically been used in the design of a telescope sunshield because it is capable of deploying in a confined cylindrical space [52].

Other applications of origami to space mechanisms include designing lightweight honeycomb structures, deployable phased array antennas, and telescopes [9,40,53]. These origami applications range from direct to abstract applications of origami. The Kresling fold pattern applied to the design of the telescope sunshield is a direct application or origami-applied design. Whereas the James Webb Space Telescope, which is not based on a specific origami fold pattern, is an abstract application or origami-inspired design.

The previous work on applying origami to aerospace mechanisms provides a preliminary foundation for future possible influences of origami to space. The NASA technology roadmaps express a need for further development in deployable antennas, decelerators, and habitats, all of which have potential origami applications that could fulfill their needs [54]. Overall, research on origami tools and design can enable new technologies for space exploration.

3.2.3 Design Process for Origami-Adapted Products

In an effort to promote and facilitate origami-adapted design a preliminary design process was developed for origami-adapted products [42]. This design process was developed based on concepts from the general design process and parallel biomimetic design processes [33]. The objective of creating a basic design process is to codify the complex, highly-coupled approach previously used to design origami-adapted products [55]. This paper seeks to show the value of the preliminary design process for origami-adapted products through examples, similar to that done with biomimetic design [56].

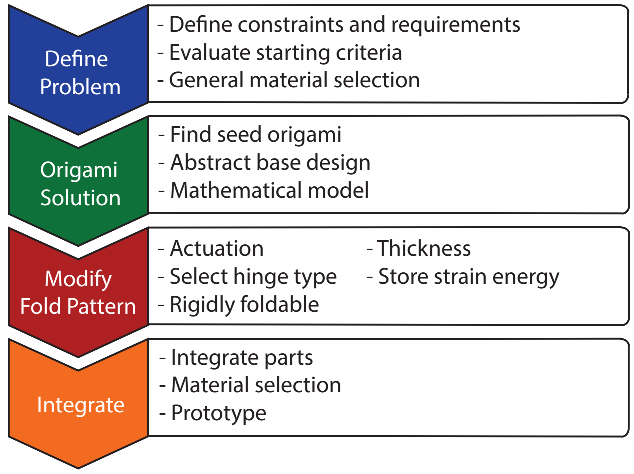

Figure 3.2: Diagram of the Preliminary Process for Origami-Adapted Products

A diagram of the process developed for origami-adapted design is shown in Fig. 3.2. The design process consists of four major steps: define problem, origami solution, modify fold pattern, and integrate. Each of these major steps has intermediate steps and tools for completing the origami-adapted design process.

To define the problem is to define the product's constraints and requirements, evaluate the starting criteria, and select the general material. Defining the product constraints and requirements is a standard step for product development, but in this case includes factors that would suggest an origami solution. To assist in determining whether origami is a good solution the following starting criteria are evaluated:

1. The product utilizes sheet-like material

2. The product has two distinct configurations

3. The product disfavors cutting and gluing (monolithic).

The starting criteria do not guarantee nor exclude origami as a solution but are a good starting point for determining whether to proceed with the design process. The last step in defining the problem is selecting the general material behavior option(s), which are: hybrid, rigid, multiple, and flexible. The main factors in selecting a general material is whether the product needs to be rigid and/or continuous. A table to help determine the general material options with descriptions is shown in Fig. 3.3 (see [42] for additional explanation).

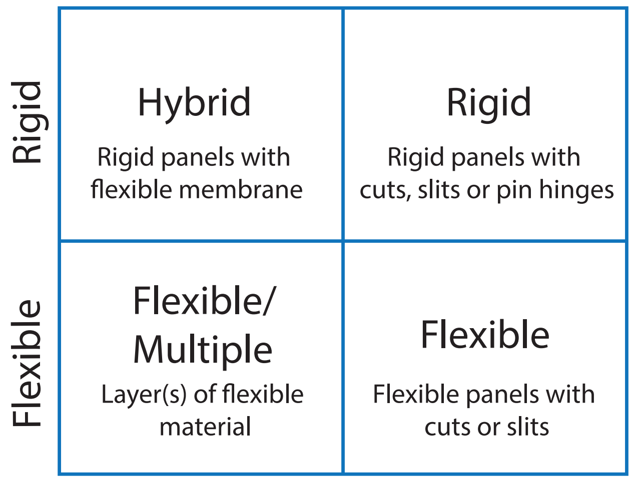

Figure 3.3: A diagram showing the general material design options and descriptions based on whether the product needs to be rigid and/or continuous.

The next step is to find an origami solution which includes finding the seed origami, abstracting the base design, and developing a mathematical model. The seed origami is the original origami pattern from which the design is based. The folds of the seed origami pattern can be altered to eliminate any unwanted features, add any missing features, and preserve the necessary features. The following design step is to create a mathematical model of the origami pattern to evaluate the design and ensure that it meets the product requirements [57].

The next major step is to modify the fold pattern. In this step, the origami fold pattern is modified to meet the product needs such as actuation method, hinge type, rigidity, thickness, and storing strain energy. Many of these design considerations are highly coupled, such as accommodating for thickness and rigidity, thus requiring iteration to find the desired result. Researchers have developed numerous tools to help address these issues [12, 14, 42, 58, 59].

The final step is to integrate all modifications and adaptations to the design together, select a final material, and prototype the design. Prototyping often occurs throughout the design process with increasing fidelity, with a higher fidelity model occurring at this point. This step overlaps with traditional product design but the end result is an origami-adapted product. This concludes the origami-adapted design process, but the design can continue to develop through testing, evaluation, iteration, and production.

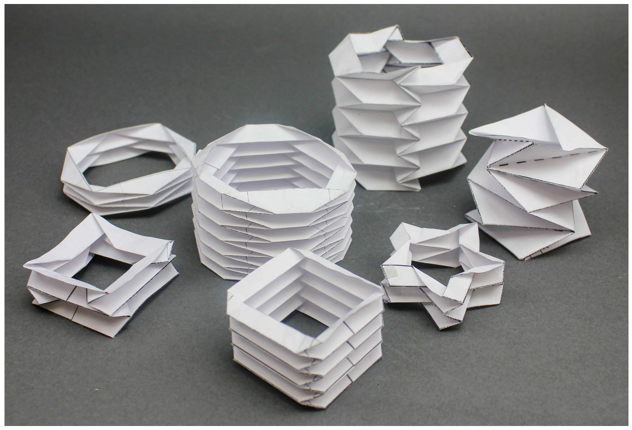

Figure 3.4: Various origami models that can be applied to a bellows.

3.3 Examples of Origami-adapted Aerospace Mechanisms

The examples for validating and testing the origami-adapted design process are an origami bellows, an expandable habitat, and a deployable parabolic antenna.

3.3.1 Example 1: Bellows

The motivation behind the origami bellows is to create a light-weight, compact bellows to protect drill shafts on future interplanetary rovers. Stainless steel metal bellows are currently used on the Mars Rover. The metal bellows have a compressibility of approximately 66%, which means that the compressed height is 34% of the fully deployed height. Developing a design that increases the compressibility of the bellows will reduce the required length of the drill shafts and thus reduce the overall weight of future Mars rovers.

Define Problem

The driving design factor is the compressibility of the bellows. Additional, design considerations include endurance of the Martian environment during the lifetime of the rover. The origami bellows must endure sand storms, thermal cycling, low vacuum, and high UV environment. The bellows must also endure 10,000 cycles in fatigue and fit in the limited space available on the rover surrounding the drill shafts.

Evaluating the starting criteria verifies that the bellows is suitable for origami-adapted design: the bellows will utilize sheet like material, has two distinct configurations (deployed and compressed), and the design disfavors cutting and gluing to create an impermeable bellows.

The general material can be determined using the requirements of the bellows. The overall purpose of the bellows is to create a barrier between the drill's shafts and the destructive Martian dust so it must be continuous. The material can either be flexible or rigid resulting in either a flexible, multiple, or hybrid material. To narrow the design space, a flexible material is chosen because it is the simplest of the options and would result in the best compression and would require the least modification to the origami pattern.

Origami Solution

Options for the seed origami are those that could function as a bellows based on their basic motions or shapes. Various possible fold patterns are shown in Fig. 3.4. Some of these patterns can be eliminated from consideration due to irregular-shaped cross sections, such as the star shaped pattern. The remaining fold options can be reduced to variations on three different origami fold patterns: the Accordion, Kresling, and Tachi-Miura polyhedron.

The Tachi-Miura polyhedron is a rigid-foldable pattern, which would reduce the wear on the bellows over time [60]. The downside of the Tachi-Miura polyhedron is that it does not maintain a constant cross section. This would cause increased strain at the clamped endpoints of the bellows. It would also be more difficult to confine the bellows within the inner and outer diameter constraints of the bellows.

A side by side comparison of the Accordion and Kresling fold patterns, their side views, and cross section are shown in Fig. 3.5, with the Kresling on the left and Accordion on the right. Both the Kresling and Accordion bellows shown are folded according to the required inner and outer diameter constraints of the rover's drill guides. Both fold patterns have several design variables such as number of sides, layers, and angle of folds. In this example, the next step in the design process, creating a mathematical model, can assist in selecting the seed origami. Mathematical models of the Accordion and Kresling patterns facilitated quantitatively comparing the two fold patterns [61]. It was found that under these constraints of inner and outer diameter, the Kresling pattern has a higher compressibility than the Accordion pattern.

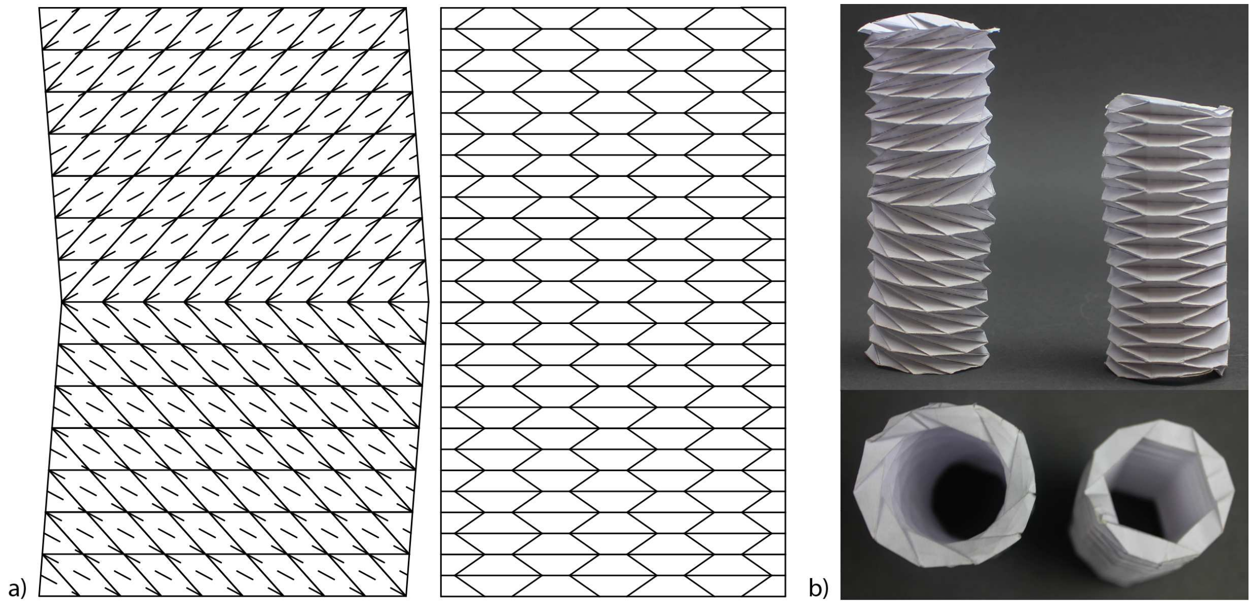

Figure 3.5: (a) The Kresling and Accordion fold patterns shown (b) folded to fit the dimension restrictions of the Mars Rover's drill shafts. Both fold patterns have the same compressed height. This visually shows that the Kresling has a higher compressibility.

The Kresling fold pattern was selected as the seed origami for the bellows design. In this example, a base design does not need to be abstracted from the seed origami because the Kresling fold pattern has the elements needed for the bellows design.

Modify Fold Pattern

In this step, the fold pattern is modified according to the design requirements. In the general material selection it was determined that a continuous, flexible material would be well suited for this design. Such materials that are able to withstand the harsh Martian environment are Mylar and Kapton which have paper-like properties and thickness, thus requiring no modification to the fold pattern to meet the product requirements.

Integrate

The final step is to integrate the Kresling fold pattern with possible materials. This completes the first iteration in origami-adapted design process. To select the final material, the bellows were subjected to testing to measure the fatigue life and environmental endurance. Figure 3.6

Figure 3.6: The Kresling fold pattern folded in Mylar, Tyvek, Kapton, and UHMWPE. These materials are possible candidates for the final material and were subjected to testing for final selection.

shows the Kresling fold pattern folded in four possible materials: Mylar, Tyvek, Kapton, and UHMWPE ready for testing. In summary, all four materials endured 10,000+ cycles in fatigue and have a compressibility of over 90%, meeting the criteria for the Mars Rover.

3.3.2 Example 2: Habitat

The second example is an expandable habitat for the International Space Station. Currently, the modules on the International Space Station are static and are shipped into space in their current configurations. Bigelow Aerospace is the first company to design and build an expandable module, which utilizes sliding wedges to expand. Another option would be to use origami to design an expandable habitat module that could collapse small enough to fit inside a rocket for transport to the International Space Station. Once attached to the station it can expand and increase the amount of usable volume.

Define Problem

The general requirements for an origami habitat is that it be airtight and have thick walls capable of protecting astronauts from radiation and flying debris. This example focuses on creating an initial proof-of-concept of a thick, rigid, expandable habitat model. In the future, higher fidelity proof-of-concept prototypes could include additional requirements.

Comparing the habitat to the starting criteria for origami-adapted design, the origami habitat uses sheet like material for the panels and it has two distinct configurations: stowed and deployed. For the last criteria, a monolithic design would be preferable for manufacturing but may not be possible for such a complex structure. The origami habitat meets two of the three starting criteria so it may not be suitable for an origami-applied design but implies it may be suited for an origami-adapted or origami-inspired design.

As for the general material selection, based on the requirements, the design option is a hybrid material. The habitat needs to be airtight and rigid. The initial proof-of-concept prototypes in this paper are shown using a rigid material without a membrane, and that a membrane would be added for higher fidelity prototypes.

Origami Solution

Origami has been used previously for earth-based habitat designs including homeless shelters, disaster shelters, and camping [62–64] . These are meant to deploy on the ground so one side is a flat surface and they are not radially symmetric. For a space habitat, a radially symmetric design is more reasonable to effectively use space during transport and gravity does not dictate a ground side of the habitat [65].

The possible origami solutions for an origami habitat are similar to those for the origami bellows. As with the bellows, the Accordion, Kresling, and Tachi-Miura polyhedron fold patterns were considered for the seed origami for the expandable habitat. All of these fold patterns are able to enclose a volume, have simple deployment kinematics, and are expandable.

The Tachi-Miura polyhedron is an attractive solution because it is a rigid-foldable pattern. The challenge of the Tachi-Miura polyhedron fold pattern is the change in cross sectional area during deployment, which goes from nearly flat to a polygon. Figure 3.7 shows a) the fold pattern and b) the deployment sequence of the Tachi-Miura polyhedron. The Tachi-Miura polyhedron fold pattern would require a complex solution to enclose the endcaps with a varying cross section.

The Accordion fold pattern is chosen over the Kresling fold pattern as the seed origami for its simplicity in creating a thick-wall design. The Accordion fold pattern can have any even number of sides with a minimum of four sides. The four-sided Accordion fold pattern is selected for its efficient use of an enclosed volume.

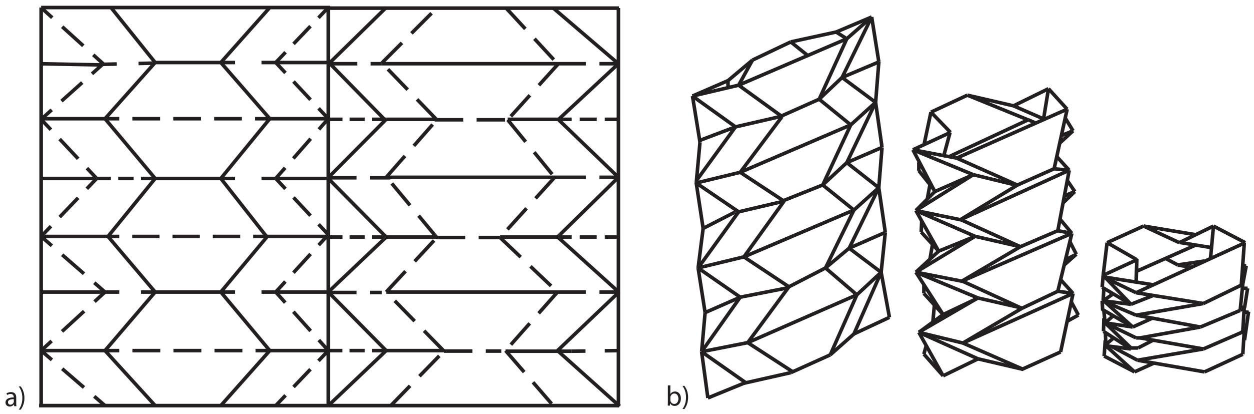

Figure 3.7: The Tachi Miura Polyhedron's a) fold pattern and b) deployment sequence.

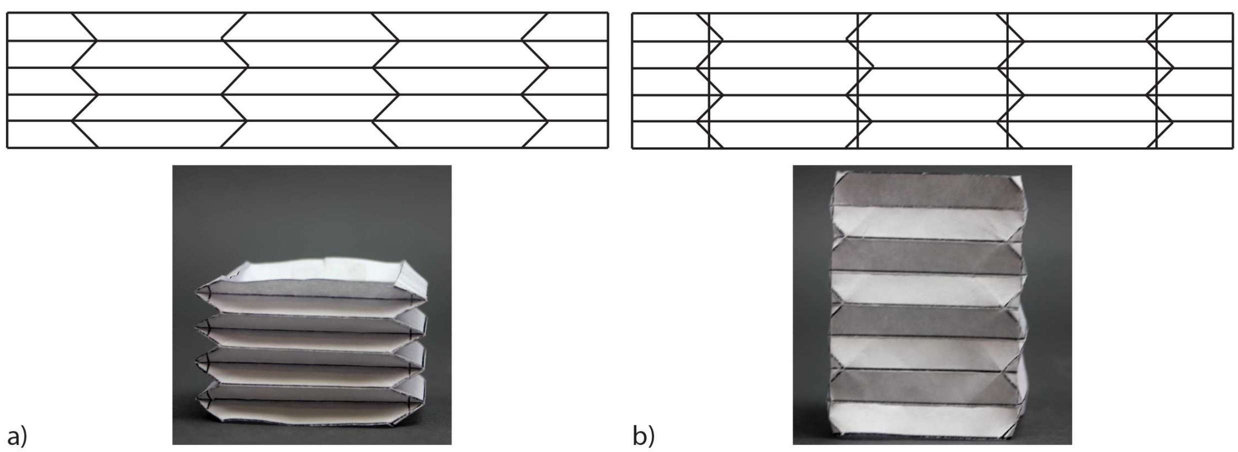

Figure 3.8: The four sided Accordion fold pattern a) without modification and b) modified with additional creases to improve its deployment.

The next step is to abstract the base design from the Accordion fold pattern to accomodate the application's needs. Figure 3.8 a) shows the Accordion fold pattern and a model in its deployed state. Adding fold lines along the vertices of the fold pattern as shown in Fig. 3.8 b) increases the expansion of the origami model. Figure 3.8 shows a side by side comparison of the models' deployed configurations, confirming that the additional creases increase expansion.

A mathematical model of the Accordion fold pattern quantifies how the thickness of the wall decreases the deployed-versus-stowed dimensions. Also, the length of the panels in each layer improves the deployed-versus-stowed length. These concepts can be visually observed but are quantified mathematically.

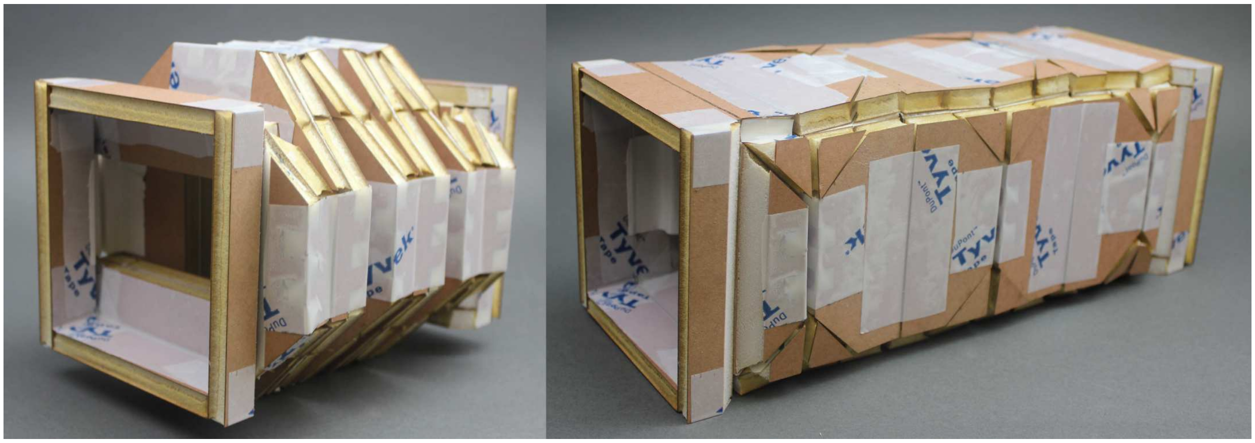

Figure 3.9: A prototype of the habitat using the modified Accordion fold pattern in thick, rigid material in both its stowed and deployed states.

Modify Fold Pattern

The next step is to modify the fold pattern to accommodate the requirements of the habitat. The two main requirements of the habitat is that it must be rigid and thick to provide protection. Therefore, the fold pattern must be modified to accommodate rigid-foldability and thickness.

Rigid-Foldability

Although the Accordion fold pattern is not rigid-foldable, a rigid Accordion prototype is able to move through its full range of motion from its stowed to deployed state. All of the deformation that normally occurs in the panels of non-rigid models is transferred into small motions at the hinges of this rigid prototype. The rigid prototype is bi-stable causing it to snap into its deployed state. As a result of full range-of-motion capability, no modifications to the fold pattern are needed to account for rigid-foldability.

Thickness

A preliminary prototype of the Accordion fold pattern was made using thick, rigid panels. This prototype showed gaps in the stowed configuration between panels. This can be fixed using one of the methods for accommodating for thickness. Some of these methods are the tapered panel method [17], axis shift method [17], membrane folds method [8], the offset panel method [59], and thick panel method [66]. The appropriateness of a given method depends on the application. In the case of the habitat, both the offset panel method and the tapered panel methods are applied. The methods are used because both are able to preserve the kinematics of the original origami model. This is especially important because it is a repeating pattern and any deviation from the original kinematics would propagate through the layers of the design. The offset panel method is used to close the gaps in the stowed configuration. The tapered panel method was used to attach rigid endcaps to the Accordion fold pattern.

Integrate

The final step is to integrate the modified fold pattern with the methods for accommodating thickness and to create a prototype. The proof-of-concept prototype is made using a thick, rigid material (Gatorfoam board) and a membrane layer can be added in higher fidelity prototypes. Figure 3.9 shows the resulting prototype in both its stowed and expanded configurations. This prototype has three repeating layers of the Accordion pattern. This prototype has an 85% increase in length and volume between the stowed and expanded configurations. Increasing the number of layers would further improve the volume percent increase. Higher fidelity prototypes may need to include additional modifications to the fold pattern such as different hinge types and include an actuation method.

Overall, this shows that origami is a possible solution for an expandable International Space Station module. This technology could improve with progressively higher fidelity prototypes.

3.3.3 Example 3: Deployable Parabolic Antenna

The last example is the deployable parabolic antenna. Parabolic antennas are difficult to transport due to their large curved shape. The larger the antenna the more efficient it is at transmitting and receiving a signal for a given bandwidth. Deployable parabolic antennas are a design challenge for space and Earth communication systems. NASA has stated that there is a need to develop, design, and increase the technology readiness level of deployable antennas [54].

Define Problem

The two main requirements for this antenna is that it be parabolic and deployable. Also, the stowed configuration should use space more efficiently than the deployed state making it more

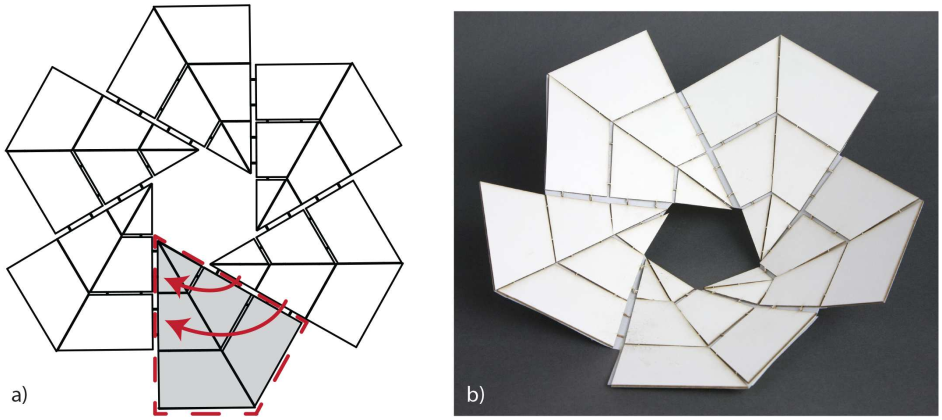

Figure 3.10: The flasher fold pattern modified to create curvature. a) To add curvature, one wedge of the flasher fold pattern is removed and the two adjacent wedges are attached. b) Prototype of the 6n-1 antenna using the 6 degree flasher fold pattern minus one wedge.

compact for transport. Additionally, it is a design goal that this antenna can be manufactured from a single, flat monolithic sheet. The challenge of this design is that parabolic shapes are not developable surfaces, meaning that they can not be flattened into a plane without distortion, but a flat sheet can be deployed to discretely approximate a parabolic surface.

The deployable antenna passes the starting criteria evaluation because it is to utilize sheet like material, it has two distinct configurations, and it disfavors cutting and gluing for a monolithic design. This does not guarantee that origami will accurately approximate a parabolic curve but it is a good candidate for origami-adapted design.

Also the requirements suggest a general material that is flexible so that it can better approximate the needed curvature. The design can either use a continuous or interrupted material design. A continuous antenna has fewer transmission losses than a non-continuous antenna. For now an interrupted, flexible material will be used and an additional continuous layer can be added in future iterations to decrease transmission losses if necessary.

Origami Solution

There are no origami fold patterns that create a parabolic shape because it is not a developable surface and can not be made from a plane surface. Instead an origami fold pattern will be selected that can be adjusted to have curvature. Often, the flasher fold pattern is used for radially deployable designs such as the origami solar panel array [8]. For that design the flasher fold pat-

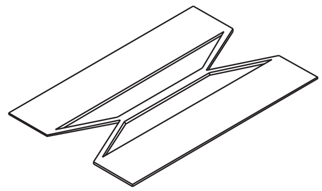

Figure 3.11: The Mixed Tension Resistant surrogate hinge to be applied to the deployable parabolic antenna design [5].

tern was modified to accommodate both thickness and rigid foldability. The modified flasher fold pattern will be used as the seed origami for the deployable antenna because it has already modified to accommodate material thickness [8].

The modified flasher pattern folds out into a flat plane. A base design for the antenna with curvature needs to be abstracted from the flasher fold pattern. To add curvature, one wedge of the modified flasher pattern is removed and the two adjacent wedges are brought together and attached, as shown in Fig. 3.12 a). Figure 3.12 b) shows a prototype of the flasher fold pattern with a removed wedge to give it curvature. This particular prototype is created from the 6 degree flasher pattern with one removed wedge which can be labeled as 6n-1 antenna. The curvature can be adjusted by using a different degree flasher pattern and removing one or multiple wedges.

For this example, a mathematical model would be advantageous to predict the curvature of the antenna but is not available at this point. Instead the curvature will be analyzed using different methods upon completion of the design.

Modify Fold Pattern

The flasher fold pattern was modified previously for rigid foldability and to accommodate for the material thickness [8]. No additional modification will be needed for these two aspects of the design especially since the design is using a non-rigid material. Modification is needed to create creases or hinges in the material that can endure large deflections while in its stowed state.

Surrogate hinges are hinges that can be created in sheet material by removing material to yield crease-like motion [12]. Surrogate hinges make it possible to have a monolithic design without being limited to paper-like materials. There are various surrogate hinge designs that are

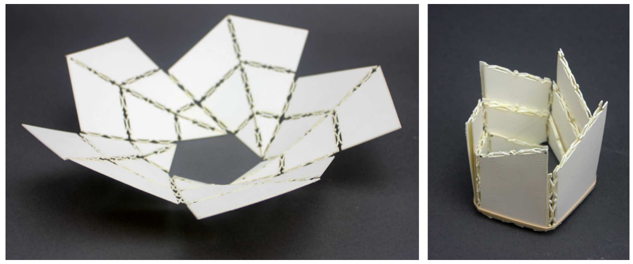

Figure 3.12: Depoyable antenna adapted from the flasher fold pattern in both its stowed and deployed states.

created by cutting and removing different parts of the material. Each of these surrogate hinges have different advantages and are selected depending on the application and design requirements.

The mixed tension resistant surrogate hinge, shown in Fig. 3.11, is selected for the design of the parabolic antenna. This hinge is selected because it can bend through large deflections and can withstand loads in tension, shear, and torsion. It is also simpler to integrate into the design because it is symmetric about the axis. The surrogate hinge can be applied to all the creases in the flasher design or only along the creases that experience the smallest radius of curvature. For creases that have larger radius's of curvature and undergo less strain, a simple ligament can be used to attach the sections instead of a complex surrogate hinge.

A design trade-off is that surrogate hinges require more area of the part but are able to go through larger deflections with less stress, thus extending the life of the product.

Integrate

The final step in the origami-adapted design process is to integrate the parts of the design and create a prototype. For the parabolic antenna, the surrogate hinge design is integrated into the fold pattern and one panel is removed to create curvature. A monolithic prototype is created using polypropylene and a single glue seam. Figure 3.12 shows the prototype in both its stowed and deployed configurations. This shows that an antenna with curvature can be discretely approximated using origami.

Two additional prototypes were created to explore the curvature of the antenna. Figure 3.13 shows three antennas with different curvatures. The antenna on the left is the 6n-1 antenna described above during the design process. The other two antennas are created using a 7 degree

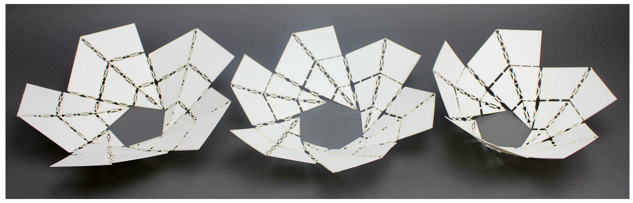

Figure 3.13: Three antennas with different curvature. From left to right they are the 6n-1, 7n-1, and 7n-2 antenna. The first number refers to the degree of the flasher fold pattern used and the second value is the number of wedges removed to give curvature.

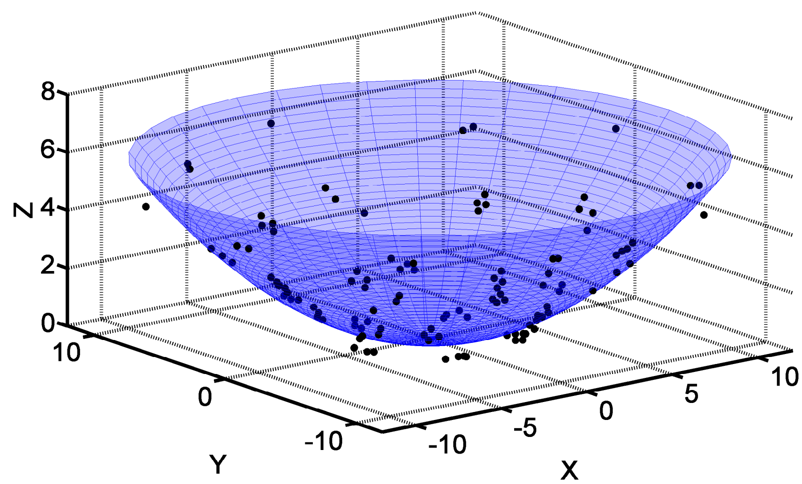

Figure 3.14: Plot of the measured vertices of the 6n-1 antenna curved fitted to a parabolic curve.

flasher fold pattern. The middle antenna has one wedge removed while the one on the right has two removed wedges giving it a smaller radius of curvature. This shows that the curvature of the antenna can be modified and tuned by varying parameters in the design process.

To evaluate the curvature of the antenna, the vertices of the panels were measured and a parabolic curve fit was made to fit the data. Figure 3.14 shows an example of the vertices of the 6n-1 antenna matched up to a curve fitted parabola. There is good agreement between the parabolic

Table 3.1: Curve Fit Data Results for the Deployable Parabolic Antennas.

	Radius of Curvature	Focal Length	R^2 Value
6n-1	31.6	7.9	0.958
7n-1	39.2	9.8	0.989
7n-2	12.7	3.2	0.989

curve and the antenna except at the vertices closest to the center of the antenna. The results of the curve fit is shown in Table 3.1 for each of the three antennas. The Table shows the radius of curvature, focal length, and R^2 value for each of the antennas. All three antennas have R^2 values above 0.95 which indicates that there is a good fit between the antenna and parabolic shape.

Despite a parabola not being a developable surface, an origami fold pattern is able to approximate a parabolic shape to create a deployable parabolic antenna. This deployable parabolic antenna is a desirable technology for both space and Earth communication systems and needs to be developed to a higher technology readiness level through further iteration and analysis.

3.4 Discussion and Conclusion

The three examples illustrate the origami-adapted design process. The design process focuses on meeting the product requirements and ensuring that origami is a good solution for the design. A comparison of design processes for the origami bellows and habitat shows that the design process is able to help a designer focus on meeting the design requirements. Initially, the possible origami solutions were the same for both products starting with the Kresling, Accordion, and Tachi-Miura polyhedron fold patterns. Following the design process resulted in the selection of different seed origami for each design based on the design requirements. The origami bellows used the Kresling because it has a higher compressibility ratio while the habitat used the Accordion because it is easier to adapt to thick materials. Both examples resulted in an origami-adapted design that fulfills an aerospace need.

The examples also showed the versatility of the origami-adapted design process. All three examples followed the four main steps: define problem, origami solution, modify fold pattern, and integrate. Not all the intermediate steps of the design process were necessary for each of the designs, but instead the design process adjusts to fit the needs of the project. The intermediate steps give the designer an opportunity to reflect on the needs of the design and whether it needs tools like a mathematical model or actuation for the success of the design. As a design increases in fidelity, often additional iteration is needed to completely modify the origami fold pattern for the design's requirements. The design process is able to meet this need. Overall, the examples illustrated the usefulness of the origami-adapted design process by following its precepts and resulting in successful designs.

The examples also demonstrated that origami is a useful tool for the design of aerospace mechanisms. The origami bellows outperforms the currently used bellows by having a compressibility ratio higher than 90% that will reduce the weight and cost of the Mars Rover. An expandable habitat for the International Space Station has yet to be implemented and would greatly increase the amount of inhabitable space without increased transportation costs. Lastly, a deployable parabolic antenna would improve the ease of transport of parabolic antennas for both space and Earth communication systems.

CHAPTER 4. HIGHLY COMPRESSIBLE ORIGAMI BELLOWS FOR HARSH ENVIRONMENTS

4.1 Introduction

Compliant mechanisms use deflection of flexible members to get their desired motion, force, or displacement. By relying on deflection to get motion instead of rigid links, compliant mechanisms can reduce complex, multi-part mechanisms into a single part. Some of the potential advantages of compliant mechanisms over traditional mechanisms include fewer parts, ease of fabrication, reduced assembly, reduced cost, reduced weight, and high precision [67]. For these reasons, compliant mechanisms are highly applicable to harsh environments like outer space. In particular, advantages that are of interest in space applications are increased precision, reduced weight, reduced friction, no lubrication, fewer parts and reduced wear [43]. The field of compliant mechanisms continues to develop as new designs are sought for increased performance.

Origami-based mechanisms are a type of compliant mechanism that is based on the art of folding paper. Creases in paper or other materials act as hinges to give motion to a single flat sheet. Origami is of particular interest in harsh and space environments for its stowability, deployability, and transportability.

Origami-based space mechanisms include antennas, solar arrays, and booms. The flasher fold pattern has inspired the design of antennas, solar arrays, sunshields, and solar sails that fold around a central hub during transport and deploy out radially for operation [8,9,41]. Other origami-based mechanisms rely on simple fold patterns like the *v*-fold to collapse long arrays or booms [68]. Some mechanisms are not adapted directly from an origami fold pattern but still have elements of folding such as the James Webb Space telescope and Lang's eyeglass telescope [40]. Origami-based space mechanisms function as deployment mechanisms, protective shields, or structural supports that are compact for transport.

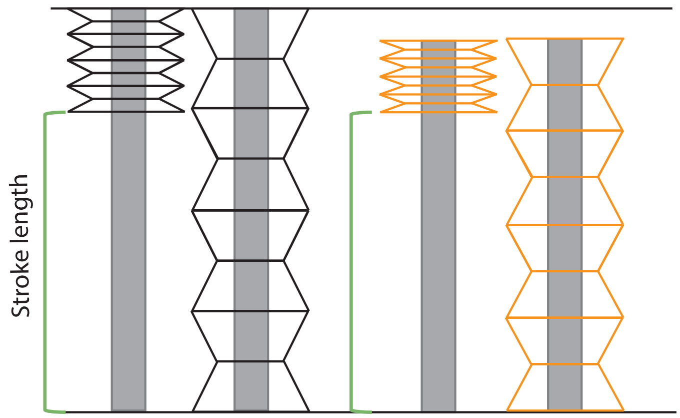

Figure 4.1: Designing a highly compressible bellows will reduce the length of the drill shaft thus reducing weight and cost of the Mars Rover.

Additional space mechanisms that have origami influences are bellows which have a wide range of applications. A bellows is a tube that can expand and contract to perform its function. Applications of origami bellows range from inflatable booms to a sunshield for a deployable telescope [48,52]. This simple structure has a large range of potential applications both in space and on Earth including as a deployment mechanism, protective shield or barrier, or as structural support.

There is a need to develop an origami bellows to protect the drill shafts of a Mars Rover from the harsh Martian environment. Currently, Mars rovers use metal bellows to create a barrier between the shafts and the dust. These metal bellows have a compressibility ratio of approximately 66%, meaning the compressed height is 34% of the deployed height. Designing a bellows with a higher compressibility ratio will decrease the necessary length of the drill shaft, as shown in Fig. 4.1. A highly compressible origami bellows that outperforms the metal bellows in compressibility will decrease the weight and cost of a rover for interplanetary exploration.

For Martian applications, the environment introduces additional requirements on the bellows besides high compressibility. The bellows must be able to withstand 10,000+ cycles at extreme temperatures, intense radiation exposure, and Martian sandstorms. This research strives to design and test a highly compressible bellows suitable for harsh environments experienced in space or during interplanetary exploration. In this application, the origami bellows acts as a protective barrier and seeks to outperform the current solution.

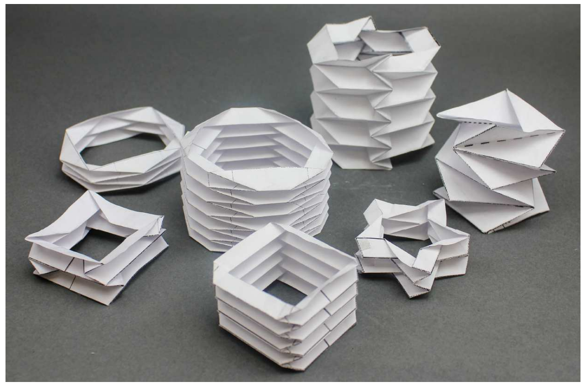

Figure 4.2: Possible origami models that can be applied to bellows.

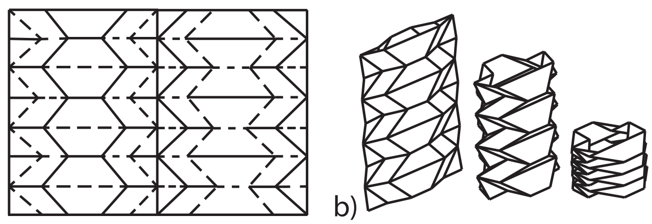

Figure 4.3: The Tachi-Miura Polyhedron, a) fold pattern and b) deployment sequence.

4.2 Design of Highly Compressible Origami Bellows for Harsh Environments

The origami bellows will be designed to be highly compressible and withstand a harsh environment. A main design variables are the origami fold pattern and the material.

4.2.1 Origami Fold Patterns

There are several possible origami models that function as a bellows; some of these are shown in Fig. 4.2. There are three distinct models: the Kresling, the Accordion, and the Tachi-Miura polyhedron. All other models are either variations of these three or impractical to fit in an annulus, such as the star-shaped bellows.

The Tachi-Miura polyhedron, shown in Fig. 4.3, is a rigid-foldable fold pattern, meaning that it experiences no strain in the creases. This means that there is little wear on the bellows during cycling. This is a desirable attribute for a fold pattern that undergoes cycling. The disadvantage of the Tachi-Miura polyhedron fold pattern is the variable cross sectional area during deployment

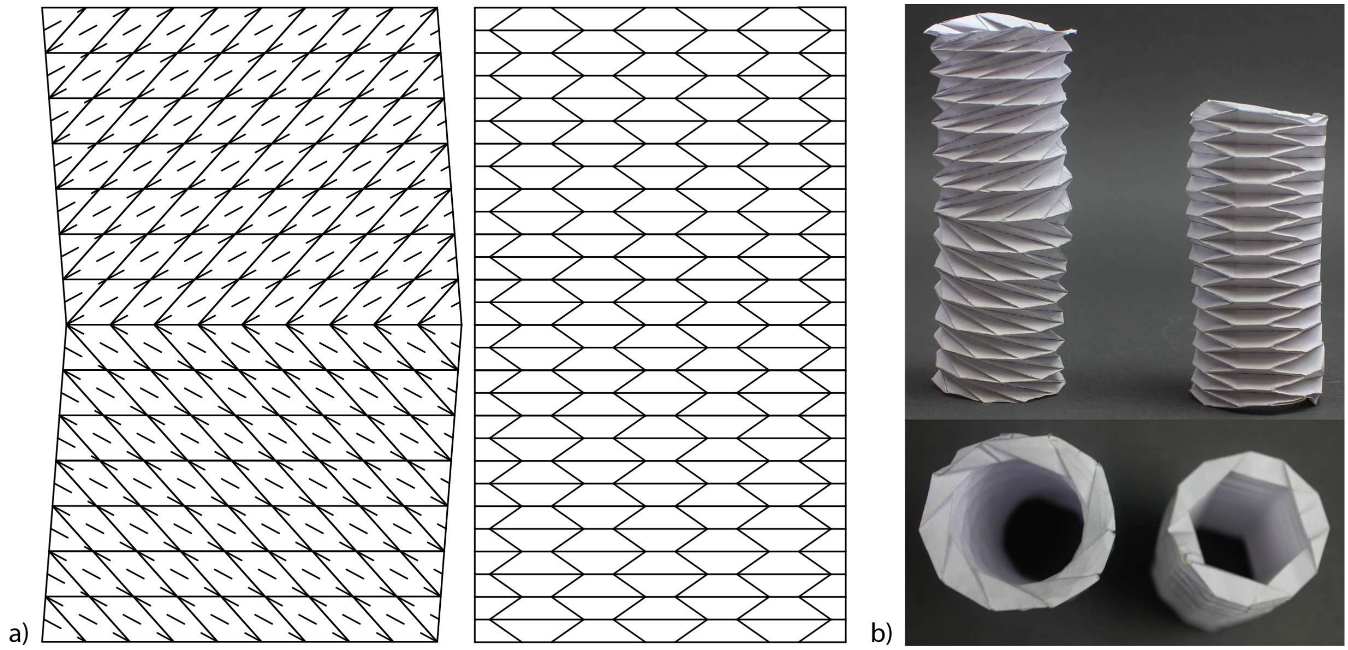

Figure 4.4: Comparison of the Accordion and Kresling fold patterns designed according to the constraints.

as shown in Fig. 4.3 part b). To serve as a bellows for the Mars Rover, the endpoints must have a constant cross sectional area for attachment purposes. Clamping these endpoints in place would cause deformation in the panels during expansion and result in additional wear. The changing cross sectional area also complicates designing the bellows to fit within the annulus constraints. For applications that do not require a fixed cross sectional area the rigid-foldable Tachi-Miura polyhedron is a viable solution that has a high fatigue life.

The two remaining candidates for the bellows design are the Kresling and Accordion fold patterns, shown in Fig. 4.4. Neither of these fold patterns are rigid-foldable and will wear in fatigue cycling. Both fold patterns maintain a constant cross sectional area and can be designed to fit within set constraints.

4.2.2 Bellows Pattern Design

The bellows' design is constrained by the outer diameter, D, the inner diameter, d, and the stroke length, L. Each bellows pattern is geometrically defined to fit the annulus of two concentric circles with the aforementioned diameters, as shown in Fig. 4.5. The remaining free variables used

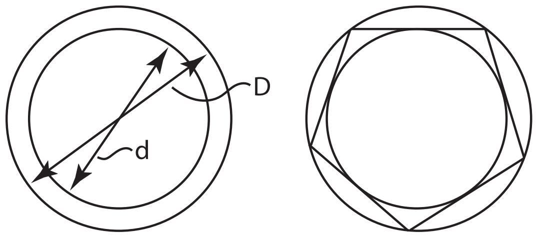

Figure 4.5: (left) Annulus formed by the two concentric circles and (right) an example of a bellows pattern fit to the annulus

to define the pattern are n, the number of tessellated sides, and s, the number of stories or layers, as labeled in Fig. 4.6. The dependent variables are the side lengths a, b, and c, and the angle ϕ, as shown in Fig. 4.7 for both the Kresling and Accordion fold patterns. For a Mars Rover, the constraints are $D = 45\ mm$, $d = 30\ mm$, and $L = 150\ mm$.

The equations defining the Kresling tessellation unit are:

$$\phi = \frac{\pi}{n}$$

$$a = D\sin(\phi)$$

$$b = D\sin(\arccos(\frac{d}{D}) - \phi)$$

$$c = \sqrt{(D\sin(\phi + \arcsin\frac{b}{D}))^2 + b^2}$$

And the equations defining the Accordion tessellation unit are:

$$\phi = \frac{\pi}{n}$$

$$a = \sqrt{D^2 + d^2}$$

$$b = D\sin(\arcsin(\frac{a}{D}) - \phi)$$

$$c = a - 2b\cos\phi$$

The Accordion tessellation unit, n, must be a multiple of two that is equal to or greater than four. This fold pattern depends on having an equal number of sides. As for the Kresling tessellation unit, n must be greater than or equal to three. These equations define the shape of each tessellation unit and the number of sides in each layer.

The next design criteria is the length of the bellows or stroke length. To reach the full stroke length, the number of stories can be increased until the deployed length minus the compacted length is greater than or equal to the stroke length ($L_d - L_c \geq L$). The deployed length is dependent on the strain in the creases. Over-straining the system increases the wear and decreases the lifetime of the bellows.

To quantify the strain that the Kresling pattern undergoes when actuated, the following equations are used to represent the strain, ε, in the valley fold side c [69, 70]:

$$c = \sqrt{(D\sin(\phi + \arcsin\frac{b\cos\delta}{D}))^2 + (b\sin\delta)^2}$$

$$\varepsilon = \frac{c - c_0}{c_0}$$

where δ is the deployment angle as shown in Fig. 4.8 and c_0 is the length of c when $\delta = 0$. The dimensionless strain energy, w, is equal to $\frac{1}{2}\varepsilon^2$. Figure 4.9 shows a nine sided Kresling unit's deployment height against the strain energy. The height of the single story is simply $h = b\cos\delta$. The maximum deployment angle, δ_{max}, can be determined by a maximum strain energy that the bellows can undergo (determined experimentally). The deployed height for a single story is then equal to $b\cos\delta_{max}$, and the total deployment of the bellows is $H = sh$.

A similar process can be followed for the Accordion fold pattern to determine the number of layers needed to achieve the required stroke length. For an analysis of the Accordion's strain, side

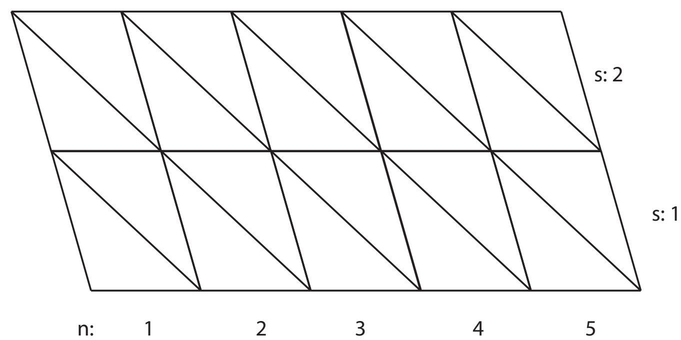

Figure 4.6: The tessellated Kresling pattern with $n = 5$ and $s = 2$

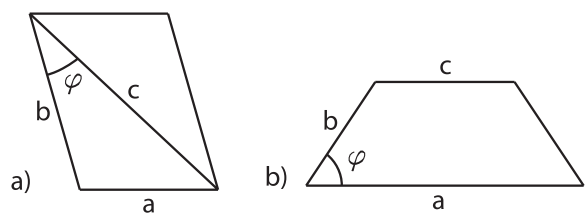

Figure 4.7: a) The Kresling and b) the Accordion tessellation units.

b is chosen as the side with the maximum strain during deployment. As the Accordion reaches full deployment and is over-strained, the vertex rolls causing additional deformation. The Accordion fold pattern is not to be over-strained to the point of causing a rolling vertex. This will cause fatigue at the vertices of the bellows leading to an early failure.

This analysis of the Kresling and Accordion fold patterns leads to origami fold pattern designs that meet the bellows' requirements for a rover. A comparison of the Kresling and Accordion fold patterns with the annulus constraint is shown in Fig. 4.4 with the Kresling on the left and the Accordion shown on the right. Fig. 4.4 part a) is the fold pattern and part b) shows a side and aerial view of the two bellows folded in paper. The Kresling has nine sides while the Accordion has six. These two fold patterns have the same compressed height with fourteen layers apiece. The Kresling has a higher compressibility than the Accordion fold pattern, meaning its deployed height is greater than that of the Accordion as can be seen in Fig. 4.4. Since compressibility is a driving factor of the design, the Kresling fold pattern is chosen as the fold pattern for the origami bellows.

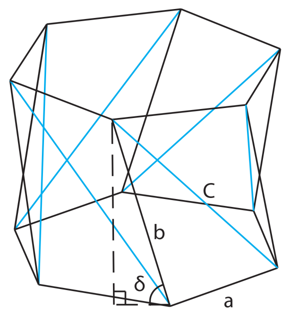

Figure 4.8: Single story Kresling showing the deployment angle, δ.

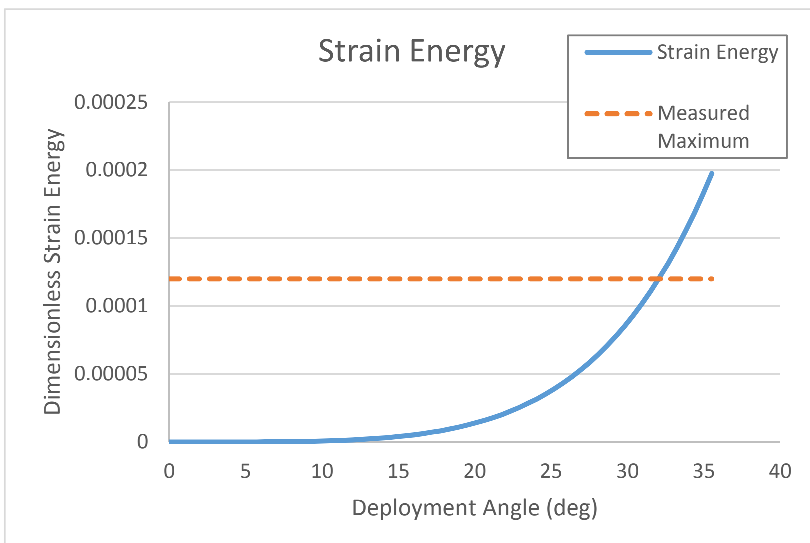

Figure 4.9: A strain vs. deployment angle plot of an $n = 9$ kresling pattern

4.2.3 Materials

Due to the harsh environment of space and Mars, the materials to be used for the bellows is of special concern. The Martian environment presents conditions of extreme cold, high UV radiation, and occasional dust storms. Other factors to consider in the material selection include folding endurance, the ability of a material to hold a paper-like crease, and the manufacturing processes that could be used with each material. Materials were chosen based on known space grade materials and materials that are good for folding origami. Space-rated materials that were

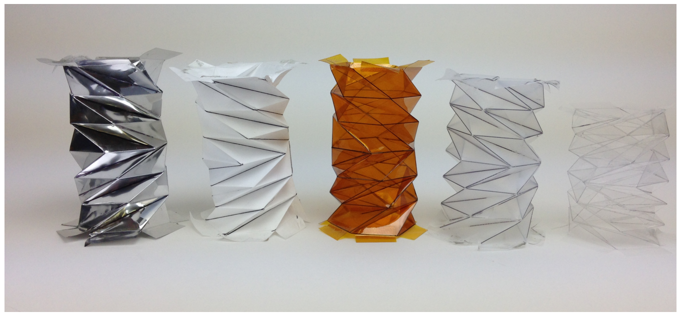

Figure 4.10: Materials to be tested in the Kresling fold pattern, from left to right: Mylar, Tyvek, Kapton, UHMWPE, and ETFE.

readily available and that have high strength characteristics are Kapton, ETFE, and Mylar. Other materials that perform well in origami applications are Tyvek and UHMWPE. These five materials were chosen to test to compare their performance in origami space mechanisms. Figure 4.10 shows the five chosen materials folded in the Kresling fold pattern with a material thicknesses of .002”.

4.2.4 Fabrication

The bellows are fabricated by hand using folding techniques. The folding is initiated in each material by first embossing the fold pattern into the material. The embossing is done by using a ball point pen and pressing firmly while tracing the folding lines printed on a separate sheet of paper. Once all of the creases are initiated using the embossing, they are folded individually to

Table 4.1: Summary of the origami bellows test results for harsh environments. The adhesive refers to both the Kapton tape and 3M Transfer Tape.

	Kapton	Mylar	ETFE	Tyvek	UHMWPE
Fatigue cycling	100,000+	10,000	Not tested	100,000+	100,000+
Fatigue after thermal cycling	30,000+	30,000+	25,000	30,000+	30,000+
Adhesive (liquid nitrogen)	fail	fail	pass	pass	pass
Adhesive (dry ice)	pass	pass	pass	pass	pass
Ablation (24 hrs)	pass	pass	pass	pass	pass
UV Radition	$>$100 Mrad	$>$1 Mrad	Not tested	Not tested	$>$10 Mrad

form sharp creases in the material. After the creases are formed, the ends of the bellows are sealed together using an adhesive.

Initially basic scotch tape was used to seal the bellows. It is evident, after some initial testing, that this tape performed poorly in both fatigue and cold temperatures and it not a suitable manufacturing method. The adhesive needs to be able to withstand the same extreme environmental conditions as the material. Two adhesives that meet the high and low temperature requirements for Mars-like environments (-70°C to 70°C) are Kapton tape and 3M Transfer Tape. The Kapton tape is a Kapton based tape with silicone adhesive. The 3M Transfer tape is an acrylic adhesive and requires overlapping sections on the bellows. The adhesive will undergo the same testing as the materials for the bellows.

4.3 Testing

The highly compressible origami bellows needs to undergo a series of testing to ensure it can withstand harsh environments. The bellows needs to endure fatigue cycling, thermal cycling, ablation, and radiation exposure. Each of the materials listed above, folded in the Kresling fold pattern, is subjected to these tests to expose its environmental limitations.

For a Mars rover, the origami bellows needs to withstand 10,000+ cycles, thermal cycling between -70°C and 70°C, resist ablation from sand storms, and not break down from intense UV Radiation. The testing will focus on ensuring the bellows can endure the Martian environment but can be applied to other harsh environment situations.

A summary table of the test results is shown in Table 4.1.

4.3.1 Fatigue

The bellows were cycled over their entire stroke length using a custom made fatigue tester as seen in Fig. 4.11. The fatigue tester consists of a crank slider mechanism attached to a motor. The bellows are attached to the slider portion of the mechanism and a base plate using an adhesive. Three cameras were placed around the bellows that periodically take pictures of the bellows during cycling to document the time of failure. A simplified Kresling pattern consisting of six sides and

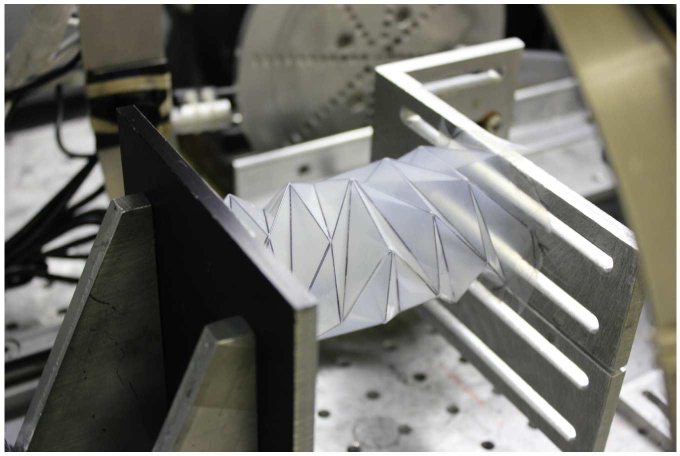

Figure 4.11: Testing of UHMWPE in the fatigue cycler.

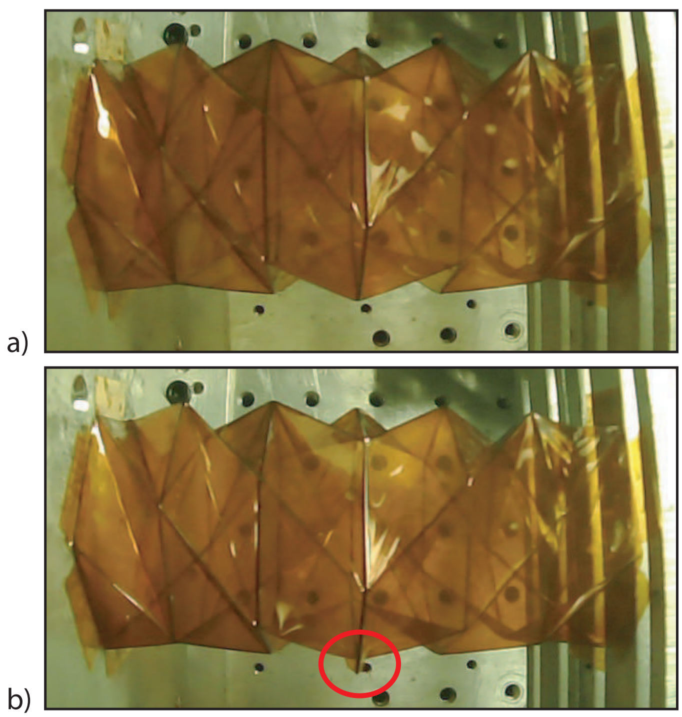

Figure 4.12: A bellows in the fatigue tester a) before and b) after failure showing that holes develop at the center vertex.

six layers was fabricated out of each material and placed in the fatigue tester until failure or 100,000 cycles to test the fatigue life of each material.

The design of the Kresling fold pattern results in stress concentrations that cause failure. The point of initial failure for all failure cases is located at the vertex in the middle of the bellows opposite of the tape seam as shown in Fig. 4.12. The vertices along the center-line differ from the rest of the bellows so it is assumed that these vertices experience the most strain. The results of the testing are shown in Table 4.1. The Mylar failed first at the required 10,000 cycles, while the rest of the materials exceeded the 10,000 cycle requirement by an order of magnitude.

4.3.2 Thermal Cycling

Mars has temp ranges from -125°C to 20°C. The origami bellows is required to withstand a temperature range of -70°C to 20°C, since it will never experience the extreme cold temperatures that occur at the Martian poles. The temperature will cycle between these two temperature extremes on a daily basis which can cause thermal fatigue leading to failure. Both the material and adhesive have to endure the fatigue due to thermal cycling.

Material

To test the thermal cycle fatigue, the origami bellows are thermal cycled between liquid nitrogen (-196°C) and ambient temperatures (32°C) for approximately 100 cycles. The liquid nitrogen is significantly colder than the set requirements for the bellows. This put additional stress

Table 4.2: Measured stress and strain of Kapton tape and material bond with no thermal cycling and after thermal cycling.

		Kapton	Mylar	ETFE	Tyvek	UHMWPE
Stress (kPa)	None	151	161	134	83	149
	Thermal	107	151	87	101	122
	% Difference	29%	6%	35%	-23%	18%
Strain (mm/mm)	None	0.11	0.10	0.15	0.20	0.13
	Thermal	0.09	0.10	0.28	0.08	0.13
	% Difference	21%	2%	-84%	60%	6%

on the bellows than necessary. After thermal cycling, the bellows were subjected to fatigue cycling. Even after thermal cycling, all the materials were able to endure over 10,000 cycles. All the materials were allowed to run to 30,000 cycles with no signs of failure except for ETFE which developed a hole at the vertex at about 25,000 cycles.

The materials endured the thermal cycling without failure but the adhesive did not. Two adhesives were tested: Kapton tape and 3M adhesive Transfer tape. Only some of the ten combinations of material and adhesive endured thermal cycling between liquid nitrogen and ambient temperature as shown in Table 4.1.

Adhesive

The Kapton tape is rated to a temperature range of -73°C to 260°C. Transfer Tape has a range from -40°C to 121°C. Neither of the adhesives are rated to temperatures as low as liquid nitrogen at -196°C. The Kapton tape and 3M Transfer Tape did not stick to Kapton or Mylar at these cold temperatures. The adhesive lost its stick after a few thermal cycles without any actuation or fatigue cycling. The other materials (UHMWPE, Tyvek, and ETFE) and tape combinations survived the 100 liquid nitrogen thermal cycles as shown in Table 4.1.

Dry ice at -79°C is closer to the lower temperature limit required for the origami bellows on Mars. The ten combinations of material and adhesive were thermally cycled between dry ice and ambient temperatures. All ten passed the thermal cycle test using dry ice. To quantify the bond strength, the tensile strength of the material and adhesive combinations were measured in an Instron. The results are shown in Table 4.2 for Kapton tape and Table 4.4 for Transfer Tape. The

Table 4.3: Measured stress and strain of 3M Transfer Tape and material bond with no thermal cycling and after thermal cycling.

		Kapton	Mylar	ETFE	Tyvek	UHMWPE
Stress (kPa)	None	255	289	73	241	138
	Thermal	153	220	76	241	135
	% Difference	40%	24%	-4%	0%	2%
Strain (mm/mm)	None	0.24	0.35	2.20	0.37	0.60
	Thermal	0.16	0.24	1.89	0.29	0.44
	% Difference	35%	33%	14%	21%	27%

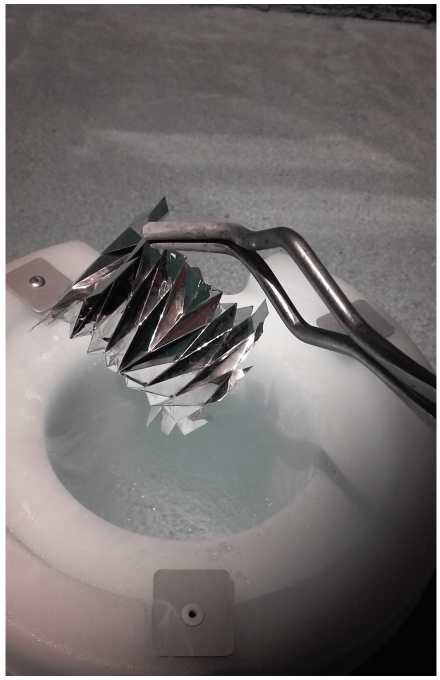

Figure 4.13: Thermal cycling the bellow's materials between liquid nitrogen and atmospheric temperatures.

tables report the stress and strain that the bond endured before failing for both without thermal cycling and the with thermal cycling.

The strength of the bond is dependent on the material and the adhesive. In general, thermal cycling weakens the bond causing it to fail at lower loads and reduces the amount of strain before failure. for a given design, material and adhesive selection should depend on the application and its requirements.

Overall, this shows that any combination of adhesive and material for the origami bellows would survive the thermal cycling experienced on a Mars rover.

Welding

As an alternative, to eliminate the thermal limitations of using an adhesive, the origami bellows can be sealed using a weld. Another advantage of welding is increasing the efficiency and accuracy of the manufacturing process, which is desirable for high volume applications. The

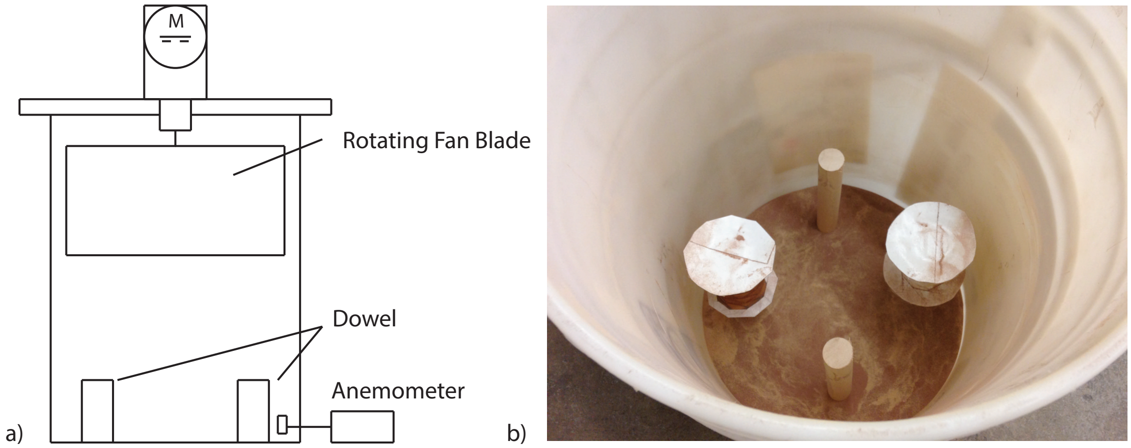

Figure 4.14: a) Diagram of the experimental setup for a mock sand storm for the ablation measurement and b) a image of the experiment.

trade-off is that welding can cause warping or distortion in the panels that can decrease the compressibility of the bellows.

For low volume applications, where compressibility is the driving design factor, welding is impractical. Thus, adhesives will be used for the rover origami bellows, but it is worth further exploration for other applications.

4.3.3 Ablation

For bellows in space, abrasive interactions with the environment is not a concern. In Martian environments sandstorms will cause abrasion. The measured wind speed on Mars ranges from 0 to 27 m/s with an average of 8.9 m/s. These winds pick up dust that scrape the surface of any exposed material on a Mars rover. Fortunately, the Martian atmospheric pressure is 168 times lower than that on Earth at 600 Pa compared to 101325 Pa. So a 27 m/s sandstorm on Mars does not have equivalent pressures as one on Earth. Still the sandstorms have an abrasive effect that can degrade a material over time.

The origami bellows was subjected to a mock sandstorm test at 14.7 psi, using Earth sand particles, at 15.6 m/s for 24 hours. The test rig is a bucket with sand particles and support dowels for the bellows at the bottom with a fan blowing running above as shown in Fig.4.14. This test is run at a higher pressure, larger sand particle sizes, and lower speeds than a Martian sandstorm. A comparison of a Mars sandstorm to the abrasive test is shown in Table 4.14. Although the test is not an exact replica of a Martian sandstorm it will give a relative comparison between the materials in an abrasive environment.

The samples' masses were measured before and after the sand storm testing. There was not a significant percentage mass change for any of the materials. Tyvek did gain some mass due to its woven fiber structure that collects dust particles. The abrasive sand does remove Mylar's outer reflective coating that reflects most visible and infrared wavelengths of light which can effect its overall performance as a material. In general, none of the materials developed any holes at the vertices or tears that would cause failure so the bellows will be able to survive a Martian sandstorm.

4.3.4 Radiation

The radiation exposure is more intense on Mars or in space compared to Earth because it is beyond the protection of the Earth's magnetosphere. This radiation causes materials to degrade over time and lose their strength properties. There are multiple types of radiation that can cause material degradation including ultraviolet light and high energy particles. The type and wavelength of radiation that causes the most damage depends on the material. A comprehensive study of material degradation due to all types of radiation in space environments has yet to be completed.

Radiation testing covering the entire UV spectrum and radiation levels experienced during a five year mission on Mars is difficult to simulate in a short time frame. This test will be foregone for initial proof-of-concept testing. Instead, information about each material's known resistance to radiation will be evaluated. Testing has been done on individual materials and specific types of radiation both in space and on Mars.

Table 4.4: Comparison of the wind speed, pressure, and particles size between Mars and Ablation test conditions.

	Average Wind Speed	Pressure	Particle Size
Mars	8.9 m/s	600 Pa	$1.47 \pm 0.21\ \mu$ m
Test	4.5 m/s	101325 Pa	2 - 64 mm

The MARIE (Mars Radiation Experiment) measured particle radiation from galactic cosmic rays and solar energetic particles. It measured an average radiation dose of 20 milli-rad per day on Mars. Over a Mars rover lifetime of 5 years that equates to 36.5 rad exposure for the origami bellows. NASA published a book stating their findings on the effect of particle radiation to various common space polymer materials [71]. This reports that Kapton can withstand >100 Mrad, Mylar can withstand >1 Mrad, and UHMWPE can withstand >10 Mrad before moderate degradation effects the material. UHMWPE is has been used for radiation shielding in spacecraft against galatic cosmic rays and solar energetic particles but breaks down due to proton irradiation [72].

Another damaging source of radiation is high energy ultraviolet radiation called UVC (100-290 nm) that is present in space and on Mars but mostly blocked by Earth's atmosphere. Kapton and Mylar are common space materials due to their resistance to degradation in high UV environments. ETFE is mostly UV transparent for the frequencies experienced on Earth and has been used as an electrical-cable-jacket in spacecraft. When exposed to space environments it discolors and begins to crack making it unsuitable for longterm missions [73]. Tyvek is not a space grade material and breaks down from UV exposure on Earth's surface. Coatings can be added to Tyvek to make it more resistant to UV.

The literature suggests that Kapton is most suited for radiation exposure while ETFE and Tyvek will degrade in extreme radiation exposure.

4.4 Conclusion

For a highly compressible origami bellows on the Mars rover, Kapton with a Transfer Tape adhesive is well suited for the application and desired lifetime. These origami bellows will be manufactured by hand due to the low volume production. Kapton is the best material for this application especially since it has been proven in space environments and is known to endure in high UV environments. The Kapton has a long fatigue life even after thermal cycling. The Transfer tape does have thermal limitations but works in the set temperature range a Mars rover will experience. Sand storms on the surface of Mars will ablate the material but will not cause punctures or holes at the vertices resulting in failure. The final design is a Kresling fold pattern in Kapton sealed with 3M Transfer Tape to protect the drill shafts on a Mars rover.

The drill shafts of a Mars rover is only one of many possible applications of an origami bellows in space or interplanetary missions. The test results can used to design any highly compressible origami bellows subjected to harsh environments. The origami bellows has proven to have a high fatigue life exceeding 100,000 cycles for some materials. Other potential harsh environmental conditions include: thermal cycling, abrasion, and high radiation which degrade the bellows material properties. The Kresling fold pattern can be designed to fit within a given inner and outer diameter and stroke length depending on the design requirements.

The information presented above for the highly compressible origami bellows for harsh environments can be used to design the bellows to fit any bellows design requirements. Origami bellows have a vast array of applications as deployment mechanisms, protective shields or barriers, or structural supports. This research shows the potential of origami bellows, their ability to outperform current solutions, and can be used as a design aid in developing more origami bellows.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The thesis presents the work done to develop and apply a basic origami-adapted design process. Origami-adapted design is a type of origami-based design. Origami-based design ranges from abstract to concrete applications of origami which can be separated into different classifications. The subsets of origami-based design are origami-inspired design, origami-adapted design, and origami-applied design. Origami-applied design is cases where origami fold patterns can be directly applied to a product's design. These have a direct correlation between origami and the emergent product. Origami-adapted design adapts origami fold patterns into products while maintaining functionality. These products move away from the ideal origami model and are more abstract. Origami-inspired design is any product that is inspired from origami which has a loose link between the emergent design and origami, including designs that simply remind one of origami through means such as geometric patterns and folding kinematics. The design process focuses on origami-adapted design which requires the greatest amount of modification while maintaining the functionality of origami.

The origami-adapted design process is based on attributes of design processes found from a variety of sources. Of particular influence is the biomimetic design process which parallels the origami-adapted design as a design process with a specific source of inspiration.

The origami-adapted design process has four steps: define the problem, identify an origami solution, modify the fold pattern, and integrate. Intermediate steps apply tools to analyze and modify the origami fold pattern according to the design requirements. The first step defines whether origami is a viable solution by evaluating a set of starting criteria. Once it has been determined that origami is a viable solution, the design process assists the designer through a series of steps that modify the origami crease pattern until the final design is reached.

The origami-adapted design process is applied to the design of three aerospace case studies: an origami bellows, an expandable habitat, and a deployable parabolic antenna. The design process is followed throughout the design of these proof-of-concept applications of origami to aerospace mechanisms.

The origami bellows is developed further with a series of testing to verify its lifetime in fatigue cycling and that it can withstand a harsh environment. The bellows is tested for a Mars-like environment in thermal cycling, abrasion testing, and high radiation. The highly compressible origami bellows passed all harsh environment testing and can be designed to accommodate other bellows applications.

This research developed a design process for origami-adapted products and demonstrated its usefulness through the design of three origami-adapted space mechanisms.

5.2 Contributions

Contributions include the research presented in this thesis and contributions to the Compliant Mechanism Research Group

Research contributions as outlined in this thesis are:

- Classification of origami-based design into origami-applied, origami-adapted, and origami-inspired design
- Development of a preliminary origami-adapted design process
- Development of a deployable parabolic antenna
- Proof-of-concept prototyping of an expandable habitat with space applications
- Design and testing of an origami bellows.

Additional contributions to the Compliant Mechanism Research Group, include:

- Team leader of two summer burst projects: Collapsible Camping Stove and Origami Bellows
- Mentor two freshman women
- Provisional patent for the Acutely Combined Torsional Hinge

- Paricipation in competitions and conferences: 3MT, Grad Expo, Space Access 2015, ASME IDETC 2014, 2015, and 2016
- Two conference papers and one submitted journal publication.

This list is not a comprehensive list of all contributions resulting from this Master's work. Countless other contributions include support for other projects, mentoring undergraduate students, and assisting with the preparation and outreach for the exhibit at the Museum of Art titled, "Folding Paper: The Infinite Possibilities of Origami."

5.3 Recommendations for Future Work

There are several recommendations for future work with regards to the origami-adapted design process and its applications. The basic origami-adapted design process can undergo a series of iterations as the understanding of origami-adapted design matures. The aerospace mechanism examples have yet to be implemented and need additional testing and iterations to further develop their design.

The origami-adapted design process needs to be validated with additional examples and case studies. A work shop is recommended to involve people outside the research group with a range of experiences and exposure to origami design. This would benefit companies and individuals who are interested in origami-based design as well as give unbiased validation of the origami-adapted design process. This can also be done using capstone or student design projects involving origami-adapted design.

One step that is not fully understood is selecting the origami source model. This is best done with previous knowledge and experience with origami and is very difficult for a first time origami-adapted designer. Designers often refer to experts in the field for developing origami-adapted designs or invest significant amounts of time gaining origami experience. This could be simplified with a searchable database cataloging crease patterns, their respective features, and examples of applications to design.

Another improvement for the design process would be to develop a better approach for modifying the fold pattern while taking account of the highly coupled systems. Often, modifying the fold pattern takes iteration because it is not fully understood how to design for actuation, thickness, rigidity, and hinge type in parallel. A deeper understanding of these design tools and their interdependency will reduce the time and iteration to modify the fold pattern.

The origami-adapted design will improve as research in origami continues to mature. The design process incorporates and depends on the origami tools developed through origami research. A more comprehensive list of available tools would improve the origami-adapted design process. It can also be updated to include new and upcoming research such as actuation methods, curved folds, and new analysis and developmental software.

All of the three aerospace examples can be further improved and developed. The origami bellows needs to be tested and validated using NASA facilities that can more accurately reflect the environmental conditions on Mars. Also, instead of doing individual testing, the bellows needs to undergo a series of testing: thermal, radiation, ablation, and fatigue to a single bellows. The accumulate wear and deformation from each test could cause premature failure.

The expandable habitat is only a proof-of-concept prototype that can be further developed. Future iterations can include: a membrane, higher fidelity hinges, and a scale model.

The deployable parabolic antenna has caught the interest of several companies and design projects that need more compact antennas for transport. A mathematical model of the antenna would be instructive for designing and tuning an antenna with specific requirements. Future prototypes can include higher degree flasher patterns, different surrogate hinges, scale models, and actual antenna materials. Another recommendation to validate that the antenna is not a cone shape is to do a parabolic curve fit to a cone and compare the R-squared values.

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APPENDIX A. IMAGING METHOD TO MEASURE ANTENNA'S VERTICES

The deployable antenna needs to be approximately parabolic to perform its function as an antenna. The interaction between surrogate hinges and panels are not fully understood and thus it is uncertain whether a computational model will accurately predict the shape of the antenna. Experimental measurement methods can determine the location of the corners of the antenna's panels without a complete knowledge of the antenna's complex interactions. Direct Linear Transformation is an imaging method used in experimental fluids to determine the x, y, and z position of a point on an object in space. This technique was used to determine the location of the corners or vertices of the antenna.

A.1 Direct Linear Transformation

Direct Linear Transformation is an imaging method used in experimental fluids to determine the x, y, and z position of an object or point on an object in space. The method uses two views of the object to determine position. There are multiple ways of obtaining two views of the object, for this application two cameras are utilized to get two separate viewpoints. Figure A.1 shows the imaging set up with two cameras placed at two different angles focused on the object of interest.

The camera images are calibrated using a calibration block, as shown in Fig. A.2. The calibration block needs to be approximately the same size as the object of interest. The block has twelve marked points with known x, y, and z locations. An image of the block is taken using both cameras. The block is then removed from the object space and replaced with the object of interest. Figure A.3 is the image of the antenna from the left camera. The antenna has twenty-two marked points at the corners of the panels that this imaging method can determine the location in three dimionsional space. Chen gives an explanation of the setup for Direct Linear Transformation and the analysis to transfer between reference frames [74].

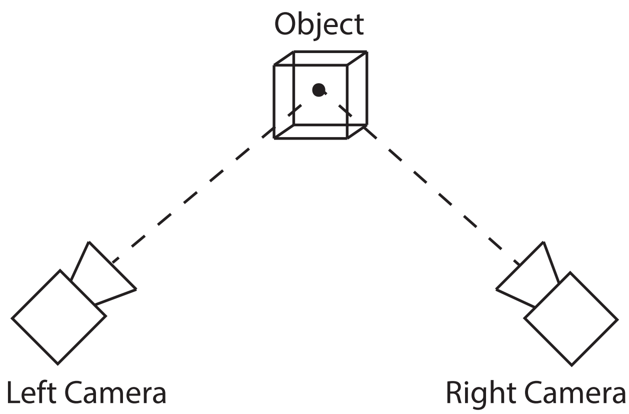

Figure A.1: Direct Linear Transformation setup using two cameras to image an object to determine the three dimensional coordinates of a point on the object.

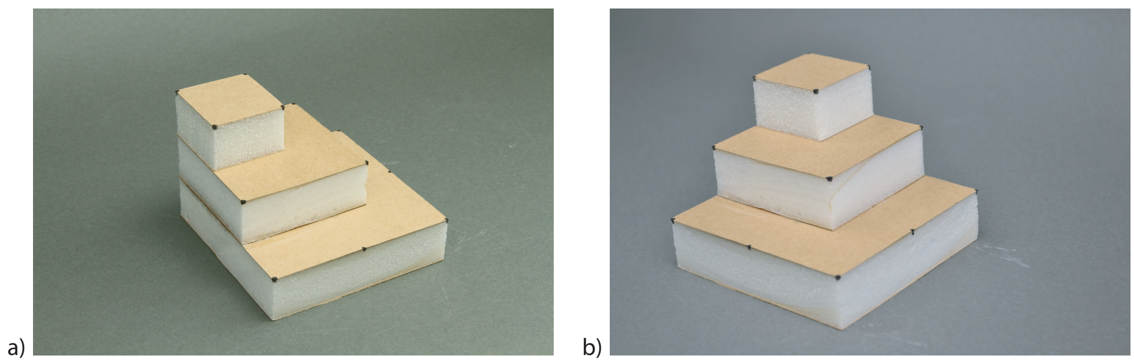

Figure A.2: Image of calibration block, with twelve points with known three dimensional positions, taken by the a) left and b) right cameras.

A.2 Analysis

The images of the calibration block and object are processed to result in a plot and positions of the points on the antenna. The direct linear transformation method only imaged a single wedge of the antenna which is then propogated to include the entire antenna. The antenna's panel corners are curved fitted to a parabolic curve to determine the actual curvature.

A.2.1 MATLAB Code

MATLAB code to analyze the four images from the Direct Linear Transformation for the 6n-1 antenna.

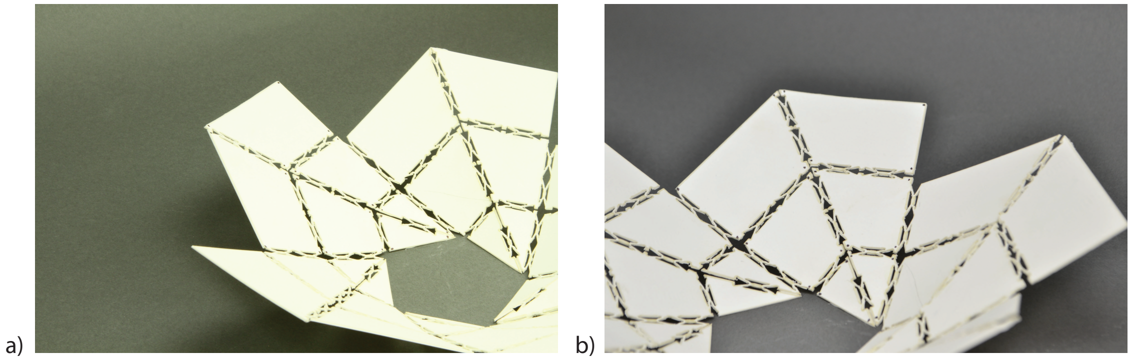

Figure A.3: Image of antenna, wtih points marking the vertices of the panels, taken by the a) left and b) right cameras.

```
% Stereo Imaging
%% Calibrate Camera
clear
close all
x_y_z_cal = [0,  0, 0;...
             4.9784,  0, 0;...
             9.9441,  0, 0;...
              3.048,  2.921, 2.54;...
             9.9441,  3.048, 2.54;...
             6.0579,   6.0579, 5.08;...
             9.9441,   6.0579, 5.08;...
             9.9441,  9.8298, 5.08;...
             6.0579, 9.8298, 2.54;...
             3.048, 9.8298, 2.54;...
             0, 9.8298, 0;...
             0, 4.953, 0];
         %input based on calibration block
%these are based on the resolution of your cameras. They are in cm/pixel
cm_pixL = 1/183;
cm_pixR = 1/151;

%The 11 columns is based off of the math. The 12 rows comes from the number
% of calibration points. This will be doubled later on
FL = zeros(12,11);
FR = zeros(12,11);
```

```
figure(1);
%input Left image calibration
imshow('J:\Research\Antenna\Imaging\6n_1_v3\block1L.JPG');
u_vL = ginput(12);   %you picking the points on the calibration block from the left camera
u_vL = u_vL*cm_pixL;    %turning pixels into cm
gL = [u_vL(1,1);u_vL(1,2);u_vL(2,1);u_vL(2,2);u_vL(3,1);u_vL(3,2);...
    u_vL(4,1);u_vL(4,2);u_vL(5,1);u_vL(5,2);u_vL(6,1);u_vL(6,2);...
    u_vL(7,1);u_vL(7,2);u_vL(8,1);u_vL(8,2);u_vL(9,1);u_vL(9,2);...
    u_vL(10,1);u_vL(10,2);u_vL(11,1);u_vL(11,2);u_vL(12,1);u_vL(12,2);];
figure(2);
%input Right image calibration
imshow('J:\Research\Antenna\Imaging\6n_1_v3\block1R.JPG');
u_vR = ginput(12); %you picking the points on the calibration block from the right camera
u_vR = u_vR*cm_pixR;
gR = [u_vR(1,1);u_vR(1,2);u_vR(2,1);u_vR(2,2);u_vR(3,1);u_vR(3,2);...
    u_vR(4,1);u_vR(4,2);u_vR(5,1);u_vR(5,2);u_vR(6,1);u_vR(6,2);...
    u_vR(7,1);u_vR(7,2);u_vR(8,1);u_vR(8,2);u_vR(9,1);u_vR(9,2);...
    u_vR(10,1);u_vR(10,2);u_vR(11,1);u_vR(11,2);u_vR(12,1);u_vR(12,2);];
close 1 2;
%% Sets up L and R matrix
k = 1;
for i = 1:length(x_y_z_cal)*2

    if mod(i,2)
        FL(i,1) = x_y_z_cal(k,1);
        FL(i,2) = x_y_z_cal(k,2);
        FL(i,3) = x_y_z_cal(k,3);
        FL(i,4) = 1;
        FL(i,5:8) = 0;
        FL(i,9) =  -gL(i)*x_y_z_cal(k,1);
        FL(i,10) = -gL(i)*x_y_z_cal(k,2);
        FL(i,11) = -gL(i)*x_y_z_cal(k,3);

    else
        FL(i,1:4) = 0;
        FL(i,5) = x_y_z_cal(k,1);
```

```
        FL(i,6) = x_y_z_cal(k,2);
        FL(i,7) = x_y_z_cal(k,3);
        FL(i,8) = 1;
        FL(i,9) =  -gL(i)*x_y_z_cal(k,1);
        FL(i,10) = -gL(i)*x_y_z_cal(k,2);
        FL(i,11) = -gL(i)*x_y_z_cal(k,3);
        k = k+1;
    end

end
k = 1;
for i = 1:length(x_y_z_cal)*2
    if mod(i,2)
        FR(i,1) = x_y_z_cal(k,1);
        FR(i,2) = x_y_z_cal(k,2);
        FR(i,3) = x_y_z_cal(k,3);
        FR(i,4) = 1;
        FR(i,5:8) = 0;
        FR(i,9) =  -gR(i)*x_y_z_cal(k,1);
        FR(i,10) = -gR(i)*x_y_z_cal(k,2);
        FR(i,11) = -gR(i)*x_y_z_cal(k,3);
    else
        FR(i,1:4) = 0;
        FR(i,5) = x_y_z_cal(k,1);
        FR(i,6) = x_y_z_cal(k,2);
        FR(i,7) = x_y_z_cal(k,3);
        FR(i,8) = 1;
        FR(i,9) =  -gR(i)*x_y_z_cal(k,1);
        FR(i,10) = -gR(i)*x_y_z_cal(k,2);
        FR(i,11) = -gR(i)*x_y_z_cal(k,3);
        k =k+1;
    end
end

L = inv(FL'*FL)*FL'*gL;
R = inv(FR'*FR)*FR'*gR;
```

```
%%}
%% Finding location within an image

%clicking on the point on the image that you want to know the actual
%location of
j1 = 24;  %number of points in the image you want to find the loation of
for j = 1:1;   %j is the number of image pairs
    %input the filenames of your image pairs
    filename1 = sprintf('J:/Research/Antenna/Imaging/6n_1_v3/6n_1L.JPG', j);
    filename2 = sprintf('J:/Research/Antenna/Imaging/6n_1_v3/6n_1R.JPG', j);

   figure(1);clf
    imshow(filename1);

    [uL, vL] =ginput(j1);
    figure(2);clf
    imshow(filename2);
    [uR, vR] =ginput(j1);
    uL = uL*cm_pixL;
    vL = vL*cm_pixL;
    close 1 2
    uR = uR*cm_pixR;
    vR = vR*cm_pixR;
%     uL(j) = uLa;
%     vL(j) = vL;
%     uR(j) = uRa;
%     vR(j) = vRa;
end
%}
for j1 =1:j1; %j1 is the number of points
    Q(:,:,j1) = [L(1)-L(9)*uL(j1), L(2)-L(10)*uL(j1), L(3)-L(11)*uL(j1);...
        L(5)-L(9)*vL(j1), L(6)-L(10)*vL(j1), L(7)-L(11)*vL(j1);...
        R(1)-R(9)*uR(j1), R(2)-R(10)*uR(j1), R(3)-R(11)*uR(j1);...
        R(5)-R(9)*vR(j1), R(6)-R(10)*vR(j1), R(7)-R(11)*vR(j1);];
    q = [uL(j1)-L(4);vL(j1)-L(8);uR(j1)-R(4);vR(j1)-R(8)];
    position = (Q(:,:,j1)'*Q(:,:,j1))\Q(:,:,j1)'*q;
```

```
    xposition(j1) = position(1,1);
    yposition(j1) = position(2,1);
    zposition(j1) = position(3,1);
end


%% Finding and Plot Position

figure
plot3(xposition, yposition, zposition)
xlabel('x')
ylabel('y')
zlabel('z')

figure
scatter3(xposition, yposition, zposition)
xlabel('x')
ylabel('y')
zlabel('z')
```