# Using Lamina Emergent Mechanisms to address needs for a Space Environment

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## Abstract

Technology that will be used in a space environment must meet certain design contraints. These include the ability to endure the harsh environment as well as be efficiently transported. The use of compliance in the design of space technologies addresses some of these issues. Compliant mechanisms are mechanisms which use the deflection of flexible members to achieve a particular motion or transmit energy. The use of deflection allows for the elimination of parts and thus reduces weight. A subset of compliant mechanisms is lamina emergent mechanisms (LEMs). They have a flat initial state with motion emerging from the fabrication plane. The purpose of this research was to identify design strategies for LEMs. We propose the use of origami and kirigami for the identification of design strategies since they are essentially LEMs.

## 1 Introduction

Lamina Emergent Mechanisms (LEMs) are designed for space—in both senses of the word. LEMs are a type of compliant mechanism fabricated from planar materials (lamina) and have motion that emerges out of the fabrication plane. Compliant mechanisms use the deflection of flexible members to achieve a desired motion, and by such eliminate parts and wear debris [5]. LEMs provide advantages in manufacturing, shipping, and assembly, since they can be made from lighter materials, fewer parts, and have a flat initial state[7]. As such they are especially suitable for applications in space exploration where every ounce and cubic inch count. LEM technologies provide a solution to the problem of what, how many, and at what price things can be taken into space.

## 2 Background

### 2.1 Designing for a Space Environment

The purpose of this research was to further understanding about the design of Lamina Emergent Mechanisms, specifically for the space environment. There are many functional requirements for any technology to be used in space. It not only must be able to endure the harsh environment of space, but must be able to be put into space in a practical way. Specific challenges include being able to endure a range of temperature regimes, weighing as little as possible, few parts, and be able to be compact. Some design concerns for products in space are listed in Table 1 along with the countermeasures that LEM technology provide[7].

### 2.2 Compliant Mechanisms

Compliant Mechanisms use the deflection of flexible members to achieve a desired motion. They provide a way to fulfill many of these functional requirements through eliminating joints, and therefore parts, by achieving the necessary motion, force or energy transmission through the deflection of flexible members. A specific branch of compliant mechanisms is

Table 1: Mapping of some design concerns for a Space Environment to the benefits LEMs provide

| Design Concerns in Space | Advantages of LEMs |
|---|---|
| friction and wear at joints | elimination of joints |
| mass and weight | part count reduction |
| transportation cost | weight reduction |
| size and volume | compact design |
| complex and costly manufacturing | planar manufacturing methods |
| tolerates impact of foreign matter | shock absorbing capability with compliance |
| expensive research and development | ability to prototype on a scaled level |

termed lamina emergent mechanisms (LEMs) which are mechanisms fabricated from planar materials (lamina) that emerge out of the fabrication plane.

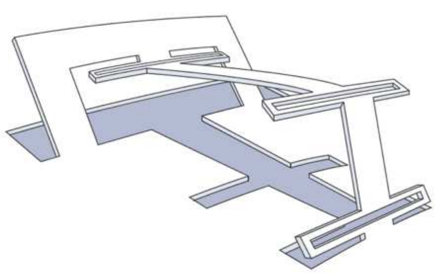

Figure 1: A sketch of a Planar Four-bar Lamina Emergent Mechanism

LEMs also provide advantages in manufacturing, shipping, and assembly, since they can be made from lighter materials, fewer parts, and have a flat initial state. As such they are especially suitable for applications in space exploration where every gram and cubic centimeter count. LEM technologies provide a opportunities to the challenges of what, how many, and at what price things can be taken into space.

**Design Challenges**

While there are numerous advantages to LEM technology, there are also inherent design challenges because LEMs are a coupled system that where function is strongly related to geometry and material properties[1]. These challenges include complexities in large, non-linear deflections, singularities that exist when leaving the planar state, and coupling of material properties and geometry in predicting mechanism behavior. A lack of design heuristics further complicates LEM design. The purpose of this research is to identify design strategies that help overcome these challenges.

## 3 Origami and Kirigami Corollaries

By identifying such strategies the design of LEMs can be extended to industry. Currently, they are a technology primarily explored in the academic world. However, there are examples of LEMs and LEM principles already used in design. For example, the joints in a LEM allow for motion in a similar way to how a fold in paper allows for motion. Some of the work in LEMs has been inspired by pop-up books, origami and kirigami since each fold that contributes to motion is in essence a joint [10, 4].

Figure 2: An example pop-up book by Sabuda.

In fact, flat folding origami and kirigami (pop-ups will hereafter be considered as part of one of these categories) are examples of LEMs since they have a flat initial state, are made from laminar materials, are compliant in nature and have motion emerging out from the plane of fabrication.

Many of the applications of origami and kirigami to the field of engineering are also LEMs. Ori- refers to fold, -kami refers to paper, and kiri- refers to cutting. Thus origami is the art of folding paper and kirigami is the art of folding and cutting paper. The art forms have been used to solve complex problems in airbag folding, stent design, space sails, and telescope design[9, 8]. Specifically these cases a compact form is necessary for transport, and there is very little, if any, ability to assemble after the mechanisms are transported. At their final location these mechanisms are deployed to their useful state. Essentially, each of these mechanisms uses the principle of orimimetics, the imitation of folding (in theory or practice) to meet the constraints of the environment[4]. As such both origami and kirigami can provide valuable insights into the design and development of LEMs, and in turn the principles of LEMs can be used to solve additional problems as well.

The impact of this research provides a new perspective into the design of adaptive morphing systems, or systems/mechanisms that morph, or change, states in their mode of use, and adapt to the environment, e.g. how the chemical compounds on an airbag react to impact and deploy it[2]. As such this research is not merely limited to designing suitable mechanisms for space, but rather extends beyond this boundary and may help approach challenges in adaptive morphing systems having applications in minimally invasive surgery, precision engineering and manufacturing, smart packaging, and deployable structures.

The following sections explain what was done, what was learned, and provide suggestions for future work.

# 4 Applying Origami Rules for Flat Foldability

Origami and kirigami literature provide insights into the design of LEMs. For systems to have a flat initial state and morph into a different state they are often constrained by their analogous rules for flat folding origami mechanisms. There are four mathematical rules relating to the production of a flat-foldable origami crease pattern, which is basically a blueprint for the construction of an origami model[3, 6]. These four rules are:

1. The crease pattern is two-colorable
2. Maekawa's theorem: at any vertex the number of valley and mountain folds always differs by two in either direction
3. Kawasaki's theorem: at any vertex the sum of all the odd angles adds up to 180 degrees, as does the sum of the even angles, and
4. a sheet can never penetrate a fold.

Previously it has been shown that a crease pattern and the graph of an origami mechanism are dual graphs of one another[4]. For the simple case of the four-bar LEM shown in Figure 3.

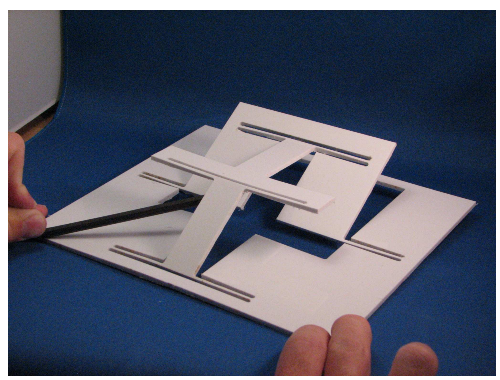

Figure 3: A Planar Four-bar Lamina Emergent Mechanism made from Polypropylene

the mechanism is two-colorable, meaning that each link can be assigned one of two colors and colored such that each color never is shares an edge with its same color. Maekawa's requirement is fulfilled as seen in the actuated figure, which has 3 valley folds and 1 mountain fold. It is believed that Kawasaki's theorem applies only to cases for spherical mechanisms where the link lengths relate to the angles between one another and follows this by definition. And finally the fourth criterion is met.

# 5 Conclusions and Future Work

Lamina emergent mechanisms are a technology suited for a space environment. As a type of compliant mechanism they reduce part count and assembly. In addition their laminar nature reduces volume and weight. LEMs can be compared with origami and kirigami. It is believed that some of the design rules for flat folding origami and kirigami are valid rules for LEM design.

Future work includes the additional exploration of origami and kirigami design to identify analogous rules for LEM design. It is anticipated that rules also exist to describe the more complex behavior and design of metamorphic and multi-layer LEMs. It is expected that they may be able to serve as guidelines for understanding the design of LEMs as well as the provide insight into the motion of LEMs and identify how and where an actuation force must be applied to achieve a desired range of motion.


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