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Identifying Potential Applications for Lamina Emergent Mechanisms and Evaluating Their Suitability for Credit-Card-Sized Products

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Identifying Potential Applications for Lamina Emergent Mechanisms
and Evaluating Their Suitability for Credit-Card-Sized Products

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

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ABSTRACT

Identifying Potential Applications for Lamina Emergent Mechanisms and Evaluating Their Suitability for Credit-Card-Sized Products

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Master of Science

Lamina emergent mechanisms (LEMs) are a maturing technology that is prepared for commercial implementation into new products. LEMs are defined by three functional characteristics; they (1) are compliant, (2) are fabricated from planar materials, and (3) emerge from a flat initial state. Advantages, design challenges, and design tools are described for each of the functional characteristics. Opportunities for LEMs are discussed, namely disposable LEMs, novel arrays of LEMs, scaled LEMs, LEMs with surprising motion, shock absorbing LEMs, and deployable LEMs. Technology push product development processes were employed to select applications for LEMs. LEM technology was characterized. In a LEM workshop, eighteen industry professionals then helped identify over 200 potential applications for the technology. The applications were evaluated, and the most promising ideas that were identified for each LEM opportunity are described with graphics of possible product embodiments.

Of the various product opportunities enabled by LEMs, deployable mechanisms – particularly in the credit card size – are among the most viable. The compactness and portability of credit-card-sized products create a strong motivation for their development. Expanding the capabilities of credit-card-sized mechanisms to include more sophisticated motions and a broader range of tasks may dramatically increase their market potential. A review of the current state-of-the-art in credit-card-sized mechanisms reveals two primary classes of mechanisms most commonly used in this form factor: rigid-body mechanisms and in-plane compliant mechanisms. The limitations of each and corresponding LEM advantages are described. Criteria for determining whether a product is a suitable candidate for using LEM technology to create or improve a credit-card-sized product are established. The advantages of LEMs in credit-card-sized products are illustrated through an example product: a compact lancing device that could be used as a main component for a highly portable epinephrine syringe.

Keywords: lamina emergent mechanisms, LEMs, compliant mechanisms, technology push, product development, credit-card-sized, Nathan Bryce Albrechtsen.

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CHAPTER 1 INTRODUCTION

1.1 Research Motivation

Lamina emergent mechanisms (LEMs) are a class of compliant mechanisms that are designed such that they can be fabricated from sheet materials (lamina) and have motion that emerges out of the fabrication plane (see Figure 1-1). LEMs share with compliant mechanisms a valuable set of advantages over traditional, rigid-body mechanisms. However, the deliberate use of planar materials and fabrication processes associated with LEMs introduces additional advantages that can further decrease cost and increase performance in particular product applications.

Although designing LEMs involves a variety of challenges, previous work has defined approaches to help overcome these obstacles. In these works, new flexures that are appropriate to sheet materials were created, modeling techniques were established, and a general design process was formed. These developments establish LEMs as a technology – a specific set of scientific and engineering knowledge applied to accomplish a desired function [1]. LEMs are a maturing enough technology that it is prepared for commercial implementation.

By leveraging the unique performance and cost-saving characteristics possible with LEMs, many innovations become possible. Improvements can be made to existing products, and new products with unprecedented performance can be created. Products that were economically impractical with other technologies could become viable in a competitive marketplace with LEM technology.



Figure 1-1: Sketch of a Spherical LEM

1.2 Thesis Objective

The objective of this thesis is to identify potential product applications for LEMs that utilize their unique attributes and to develop a set of criteria for determining whether a potential product application is a suitable candidate for using LEM technology to create a credit-card-sized product. Technology push product development processes will be used to accomplish this objective. After characterizing LEM technology, identifying potential applications for LEMs, and evaluating the applications, the best applications from the evaluation will be described and discussed. Credit-card-sized mechanisms will be established as an area where LEMs can expand on the capabilities that currently exist due to their ability to be extremely thin and compact, yet have sophisticated, out-of-plane motions. Criteria for determining whether a product is a suitable candidate for using LEM technology to create a credit-card-sized product will be developed. A preliminary design and prototype for a credit-card-sized LEM lancing device will be discussed as an example of the expanded performance capabilities of LEMs in the credit card form factor.

1.3 Thesis Outline

This outline describes the flow of the chapters in the thesis. Chapter 2 reviews previous work in LEMs by characterizing the advantages, challenges, and design tools associated with each of the three functional characteristics of LEMs. A discussion of opportunities for LEMs that stem from the functional characteristics is provided. Technology push product development processes are also reviewed. Chapter 3 describes a workshop that was conducted to identify potential applications for LEMs. Several potential applications of LEMs are described for each LEM opportunity. The content of Chapters 1 through 3 is from a paper to be presented at the 2010 ASME Design Engineering Technical Conferences [2]. Chapter 4 establishes LEMs as a means for expanding the capabilities of credit-card-sized mechanisms, and develops the criteria for whether a product is suitable for using LEMs to create a credit-card-sized product. Chapter 5 presents a design and prototype for a credit-card-sized LEM lancing device. Much of the content from Chapters 4 and 5 are intended for submission to a 2011 conference. Chapter 6 presents thesis conclusions and describes recommendations for further research.

CHAPTER 2 BACKGROUND

2.1 Introduction

An understanding of LEM characteristics, with their associated advantages, challenges, and design tools, provides a foundation for this thesis. The advantages of LEMs enable many opportunities for particular classes of products. Previous work with LEM applications is discussed. Technology push product development processes compose the primary research method for this thesis. A review of these processes is also provided.

2.2 LEMs

LEMs are defined by three functional characteristics. LEMs (1) are compliant, (2) are fabricated from planar materials, and (3) emerge from a flat initial state. All other attributes of LEM technology originate from one of these functional characteristics (see Table 2-1). Each functional characteristic brings benefits to LEMs, and a description of these advantages is provided. The functional characteristics also introduce intrinsic challenges; however, design tools have been developed to address each of the challenges in LEM design. Explanations of these design challenges with their respective solutions are presented to show that the technology is prepared for integration into commercial products. Finally, by combining advantages from the functional characteristics in different ways, many opportunities arise for LEM technology. A discussion of these opportunities is provided.

Table 2-1: Functional Characteristics, Advantages, Design Challenges, and Design Tools of LEMs

Functional Characteristic	Advantages in LEMs	LEM Design Challenges	LEM Design Tools
Compliant	<ul style="list-style-type: none"> • Reduced Assembly • Energy Storage Potential 	Non-Linear Deflections	Pseudo-Rigid-Body Model
		Induced Stress	Flexibility Relations
Planar Manufacturing	<ul style="list-style-type: none"> • Low Cost • Micromachining 	Geometrically Constrained Flexures	Planar Flexures
Flat Initial State	<ul style="list-style-type: none"> • Compact • Complex Motion Emerges from Simple Topology 	Change Point	Metamorphic Mechanisms
		Coplanar layout	Ortho-Planar Mechanism Design Process

2.2.1 Compliant

LEM s are compliant mechanisms because they achieve motion by deflecting flexible members [3].

2.2.1.1 Advantages in LEMs

Although compliance can introduce numerous advantages in mechanisms, there exist two primary advantages that add significant value in LEM applications. First, because traditional joints with multiple pieces are replaced with a monolithic flexure, assembly can be dramatically reduced or eliminated. This reduces the overall cost of manufacture. Also, the compliant nature of LEMs induces energy storage during motion. This stored energy is referred to as distortion energy, and equations for its behavior are established [4]. Energy storage in LEMs could be useful in many applications.

2.2.1.2 Design Challenges and Tools

LEMs undergo the large deflections found commonly in compliant mechanisms; thus, designing LEMs requires non-linear deflection analysis. Analytically accounting for geometric non-linearities leads to elliptic integrals; however, the pseudo-rigid-body model is a simple approximation that is commonly used in analyzing large displacements [3]. This simplified analysis can be an effective design tool for LEMs.

Using compliance in LEMs also couples motion with stress. This could be advantageous in some situations because it creates barriers to reverse engineering [5]. However, this is often a design challenge because it limits deflections, precluding the continuous rotations that are available with traditional rigid link joints. Relationships governing stress and flexibility in a joint are well-developed design tools. Both stress and flexibility can be manipulated by changing a mechanism's geometry (width, thickness, length, and cross section shape), material properties, or boundary conditions [6].

2.2.2 Planar Manufacturing

LEMs are manufactured from sheet materials, which are also referred to as lamina.

2.2.2.1 Advantages in LEMs

A wide range of planar manufacturing methods are available, such as stamping, fine blanking, water jet cutting, wire electrical discharge machining, and laser cutting. Some of these processes, especially stamping, offer significant cost advantages when used in large-scale production. A mechanism that can be completely processed with stamping can have an extremely low cost.

The planar fabrication of LEMs also enables the use of layered micromachining techniques similar to those used in the manufacture of microchips. These processes include LIGA [7], surface micromachining [8], and anodic bonding [9],[10].

2.2.2.2 Design Challenges and Tools

Because LEMs are fabricated from planar materials, planar flexures are optimal. Many joints that are suitable for LEMs have been identified [11]. The lamina emergent torsional joint has high flexibility and can be fabricated from a single layer of material without requiring a reduction in thickness. Equations governing the joint's stiffness and stress have been developed [12]. Flexures that are particularly suited for metals have also been created [13].

2.2.3 Flat Initial State

The motion of LEMs emerges out of the initially-flat, fabricated state.

2.2.3.1 Advantages in LEMs

In their initial state LEMs are ultra compact. Some LEMs may be formed slightly out of plane during fabrication. Even so, these mechanisms can be shipped compactly by stacking them for transport [14]. The flat initial state also causes LEMs to have a very simple, generally two-dimensional, topology. This can be advantageous because the complex motions of LEMs can be surprising as they emerge from their flat state.

2.2.3.2 Design Challenges and Tools

Because all of the links in the pseudo-rigid-body model [3] of a LEM are coplanar in their initial flat state, LEMs meet the criterion for a special-case grashof mechanism [15], or

change-point mechanism. The criterion is that the sum of the lengths of the shortest and longest links is equivalent to the sum of the lengths of the other two links of a four bar mechanism. This means a LEM in its flattened state can have motion that is unpredictable [16].

For LEM applications where unpredictable motion is undesired, work in compliant ortho-planar mechanisms has demonstrated that metamorphic LEMs are one workable solution to the change-point problem [17]. A metamorphic mechanism is a “mechanism whose number of effective links changes as it moves from one configuration to another” [18]. By morphing a LEM, the number or lengths of its effective links can be changed to no longer meet the criterion of a special-case grashof mechanism [19],[20].

Another challenge that is presented by having a flat initial state is that the topology must allow all links in a layer to simultaneously lie in a plane without overlapping. Work in ortho-planar mechanisms has established an approach that can be used to design LEMs. This approach includes a step dedicated to designing a planar configuration and has examples of possible layouts [17].

2.3 Enabled Opportunities for LEMs

By combining the advantages of the different functional characteristics of LEMs, various opportunities that are enabled by LEMs become evident (see Table 2-2). Descriptions of these opportunities are below.

2.3.1 Disposable Mechanisms

By using low-cost, planar manufacturing techniques to create mechanisms with little or no assembly required, production of LEMs can be very inexpensive. Flat initial states can further

Table 2-2: Enabled Opportunities of LEMs

Functional Characteristic	Enabled Opportunities					
	Disposable	Novel Arrays	Scaled	Surprising Motion	Shock Absorbing	Deployable
Compliant	X	X	X	X	X	
Planar Manufacturing	X	X	X			
Flat Initial State	X	X		X		X

reduce costs through compact shipping. Such low-cost mechanisms could be considered disposable.

2.3.2 Novel Arrays of Mechanisms

An array in this context is defined as a patterned arrangement, normally in rows and columns. LEMs that are composed of an array of mechanisms could benefit from all three functional characteristics. If a large array with many mechanisms were to require manual assembly, the labor costs associated with production might preclude that product from becoming economically viable. By using a stamping process, eliminating assembly through compliance, and transporting compactly in the flat initial state, price can be reduced significantly. LEMs may enable many novel arrays that were previously cost prohibitive.

2.3.3 Scaled Mechanisms

The planar fabrication and potential to eliminate assembly through compliance allows for scaling to very small sizes. Using micromachining techniques, LEMs can be developed on the micro scale. In addition, mechanisms that have been developed at the micro level can be scaled to fit larger applications.

2.3.4 Mechanisms with Surprising Motion

LEM designs can have complex, unusual, and non-intuitive motion. A flat initial state causes LEM designs to have a very simple topology, and compliance allows LEMs to be monolithic. Therefore, the complex motion emerging from a single sheet of material is often surprising and impressive to users.

2.3.5 Shock Absorbing Mechanisms

The compliant nature of LEMs induces energy storage during motion. Not all of the energy is stored in LEMs. Some of the energy can be dissipated by conversion into heat and friction, giving LEMs an ability to dissipate energy as well.

2.3.6 Deployable Mechanisms

LEM designs can be transported in their flat initial state and then deployed onsite into an expanded configuration. This has the potential to dramatically increase portability and decrease the cost of handling, storing, and shipping LEMs.

2.4 Previous Work with LEM Applications

Although the technology is a new development, some mechanisms already exist that fit the definition of LEMs. The existence and success of many of these mechanisms in the marketplace attest to the viability of LEM technology.

2.4.1 Paper Mechanisms

Numerous paper LEMs are in wide use today. Origami objects are LEMs because they are created by cutting and folding paper [21],[22]. Origami has even been identified as a possible candidate for making stents [23]. Pop-up mechanisms, most often used in children's books, are common LEMs in the market today [24-26]. Most corrugated packaging can also be categorized as LEMs [27].

2.4.2 Sheet Metal Mechanisms

Some sheet metal LEMs have also been developed. Metal hair barrettes are an example of a bistable LEM. Metal, compliant ortho-planar springs are also LEMs; they have been used in industrial valves and in continuously variable transmissions for all-terrain vehicles [28],[29]. Research has also been done to design metal flexures [13].

2.4.3 Microelectromechanical Devices

Microelectromechanical Systems (MEMS) are microscopic mechanisms. Many MEMS emerge from the fabrication plane, causing them to be LEMs. These include video projection systems, actuation systems for micromirrors and MEMS-based light modulators [30-32].

2.5 Technology Push Product Development

Most product development is done through market pull processes, in which customers describe their needs, and a product is designed to meet those needs using existing technologies [33]. To find applications for a new technology, a technology push product development process is more appropriate. Technology push product development is a structured approach that bridges the gap between the development of a new technology and its integration into a successful product. This approach can be used with LEMs to effectively identify products where the advantages of the technology can be most beneficial.

2.5.1 Advantages of Technology Push

Technology push processes provide important steps for selecting technology applications that are not included in market pull processes, such as identifying industries for application and evaluating different projects for development. By using technology push, breakthrough markets can be created that dramatically change consumer purchasing habits. Xerography (photocopying), microprocessors, digital displays, microwaves, post-it notes, and fiber optic cables all originated from technology push processes [34].

2.5.2 Challenges in Technology Push

Working with technology push is often more difficult than designing with a market pull strategy. Because product design is precipitated by a technology instead of customer requests, a market must be developed for technology push products. This also makes identifying customer needs challenging for designers. New technologies can have multiple potential applications, but resources can only be committed to the most promising projects. Using technology push process models addresses these issues.

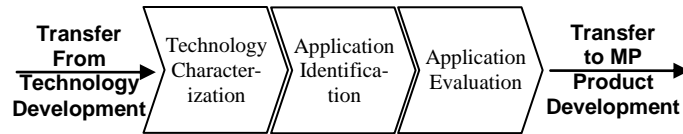


Figure 2-1: A Basic Model for Technology Push Product Development [35]

2.5.3 Technology Push Product Development Process Model

Until recently, detailed process models for technology push product development did not exist. Research has been done to develop a process model for technology push. The basic technology push model consists of three main phases (see Figure 2-1). After a new technology is developed, the first phase is to characterize the technology. This is done by delineating the functional characteristics, advantages, and challenges of the technology.

The second phase in technology push is to identify potential applications for the technology through focused brainstorming. Using a network of broad-based technologists in this phase helps to identify diverse applications and begin developing market awareness for the new technology [34].

The third phase of technology push is to evaluate the potential applications that have been identified in order to select projects for further development. It is accepted and more efficient to use a progressively exclusive evaluation process in which products that do not score sufficiently high in one of the categories are not scored in the remaining categories [36]. Selected concepts can be transferred to a more traditional market pull process for further development.

2.6 Conclusions

LEMs have many advantages that stem from their functional characteristics. Design tools have been created for many of the challenges of LEM design, so LEM technology is prepared to

be integrated into commercial products. It has been shown that there are six main opportunities enabled by the advantages of each LEM functional characteristic. Some products already exist that leverage LEM advantages, but more work can be done to deliberately utilize the unique opportunities of LEMs. Technology push product development models are a structured approach to identifying and evaluating applications for LEM technology.

CHAPTER 3 USING TECHNOLOGY PUSH FOR LEMS

3.1 Introduction

Technology push product development processes were used to identify and evaluate LEM applications. The three phases of a technology push product development process – technology characterization, application identification, and application evaluation – were executed for LEMs. The most promising ideas for each LEM opportunity will be presented here.

3.2 LEM Characterization

To begin the technology push product development process, technology characterization was performed. This involved defining the functional characteristics, advantages, challenges, design tools, and enabled opportunities for LEM technology as shown previously.

3.3 Application Identification

Next, to identify a broad range of potential LEM applications, a workshop was organized that included industry professionals in the technology push process. Eighteen broad-based technologists from industry, including engineers from aerospace, semiconductor manufacturing, defense communications, and medical companies, along with patent attorneys, industrial designers, entrepreneurs, and outdoor lead users, were in attendance (see Appendix A). LEMs were described to the attendees using the technology characterization. Prototypes, current LEMs in the market, previous LEM research, and technology push product development processes were

also reviewed. During the ensuing period of focused brainstorming, the broad-based technologists identified potential uses for LEMs from their own perspective. Through two workshop sessions, over 200 potential uses for LEM technology were described. Additional sessions were held in the Compliant Mechanisms Research Group. The resulting applications are included in Appendix B.

3.4 Application Evaluation

After the workshop, the potential applications were evaluated using the progressively exclusive scoring process described previously. Assessment was based on the following three factors: the degree to which the technology is utilized, the value added by the technology over existing products, and the likelihood of developing a successful product. The most promising ideas are those that scored well in all three areas, and these applications are described below. Note that this work does not attempt to be comprehensive in identifying the possible applications for LEMs; however, it does provide a broad view of the potential impacts of the technology.

3.5 Potential Applications for LEMs

The LEM applications can be meaningfully organized by function, intended market, or LEM advantages. In keeping with the technology push approach, they are organized here according to the LEM opportunity that offers improvements over alternative products. Many of these applications leverage multiple LEM advantages to improve the existing product. In those cases, they are organized according to the LEM characteristic that adds the most prominent advantage to the product.

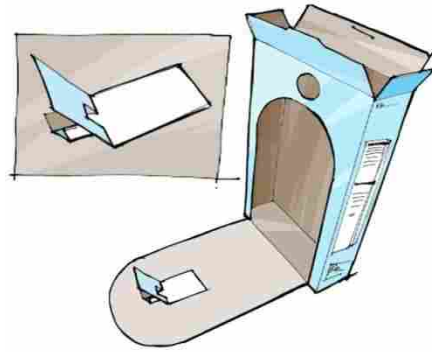


Figure 3-1: Cereal Box Packaging Used to Make Entertaining Games for Children

3.5.1 Disposable Mechanisms

There are many possible applications for disposable LEMs. Sterile products could use emerging packaging so that opening the packaging causes a motion to present the non-sterile end to the user for easy removal. Cereal boxes and other cardboard packaging could have LEMs that emerge into entertaining games for children (see Figure 3-1).

Radio frequency identification is becoming more common in credit cards, allowing users to complete transactions more quickly and easily. However, this can also be a source for identity theft by scanning a card in someone's pocket. A LEM could be used as a credit card faraday cage to cover the chip until the device is deployed for use (see Figure 3-2). Alternatively, the receiving or signaling circuits could remain open until the user actuates a LEM to make electrical contact during a credit card transaction. The low cost of these devices allows companies to mail credit card offers that are often viewed as disposable.

3.5.2 Novel Arrays

LEM arrays are perhaps the largest group of potential applications for the technology. A LEM printed circuit board could integrate a QWERTY keyboard with its

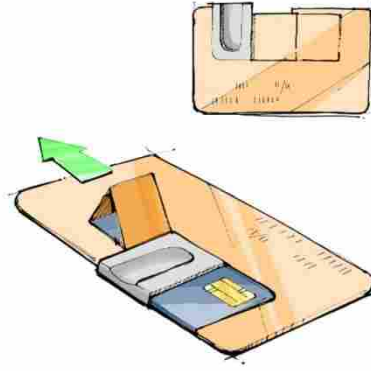


Figure 3-2: A LEM Faraday Cage Covering the RFID of a Credit Card to Prevent Identity Theft

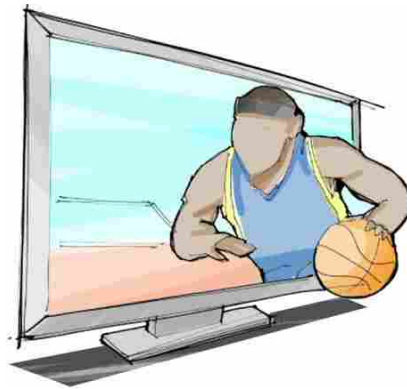


Figure 3-3: A Television Where Each Pixel Is a LEM, Creating a Three-Dimensional Image

underlying circuitry into a single piece device. A television screen in which each pixel could emerge from the viewing plane would create a more exciting three-dimensional experience (see Figure 3-3). A similar array could be used to give tactile responses to users in a virtual reality environment.

LEM arrays would experience widespread use if applied to electricity generation. Energy could be harvested from urban pedestrian traffic, wind, waves, or highway pavement compression.



Figure 3-4: A Guided Array of Solar Panels Mounted on a Vehicle

Creating an array of small surfaces that can be oriented to face in different directions would be useful in many application areas. A guided LEM solar array would dramatically reduce the bulk of current solar trackers, perhaps allowing them to be mounted on the surfaces of vehicles or buildings (see Figure 3-4). A directional array could be used to reflect, combine, and diffract various media such as waves, signals, or light, possibly allowing the creation of dynamic acoustics, radar-diverting stealth surfaces, improved satellites, or artistic lighting effects. The mechanism would even have the ability provide a variable surface texture. This might be used to manipulate drag characteristics for guiding projectiles, create air resistance for rapid braking, or regulate flow rates in pipes. It could also be used to change the traction of contact surfaces.

LEM arrays could become powerful tools to influence thermal properties. By stacking layers of LEMs, a kinetic insulation could be possible. Deploying the mechanisms would increase the amount of air contained in the insulation, thereby increasing the thermal resistance. This is advantageous over existing kinetic insulations because it only requires a simple mechanical input instead of pressurization [37]. The layers of LEM insulation could even be reconfigured into heat fins, converting the device from a heat shield into a heat sink (see Figure 3-5).

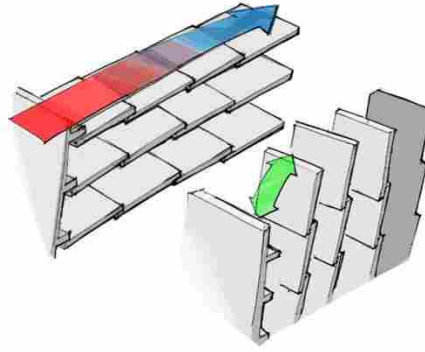


Figure 3-5: LEM Heat Fins That Can Be Reconfigured into Insulation

Deployable rebar structures are another application that could benefit from a pattern of co-planar joints. Current rebar structures require extensive manual assembly that consists of fastening rods together using wire and hand tools. Instead, large sections of rebar structures could be stamped and deployed into the desired configuration with one or two simple inputs. This could dramatically reduce labor costs and the duration of construction projects, which may be particularly important for rebuilding after a disaster.

3.5.3 Scaled Mechanisms

Because LEMs are a scalable technology, MEMs with motion that emerges from the fabrication plane might become more common. Autonomous MEM devices could perform various operations on individual cells. Cells could be physically manipulated, tested for various diseases, and individually medicated. A large number of micro cutting mechanisms in the bloodstream could erode plaques from arterial walls, avoiding the need for invasive stents or bypass surgery (see Figure 3-6). Similar mechanisms could be used to clean industrial piping. The devices could be removed from the process with magnets to maintain production rates.

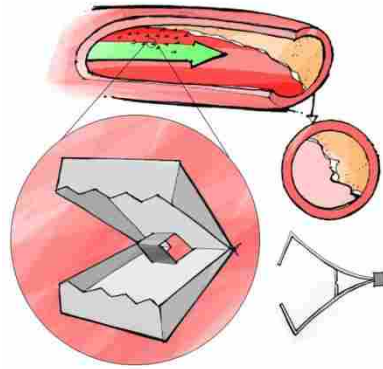


Figure 3-6: Microscopic LEMs Placed in the Bloodstream to Remove Blood Vessel Plaques

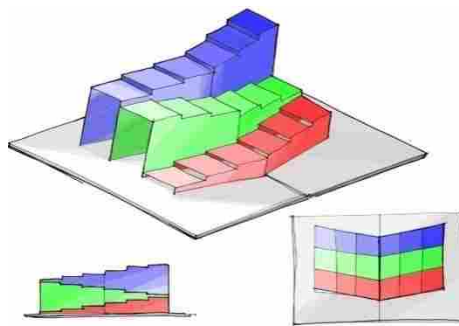


Figure 3-7: A Surprising Three-Dimensional Board Game Made with a LEM

3.5.4 Surprising Motion

The complex motion that springs from a simple LEM can surprise users and attract attention. This could be used in pop-up advertising that deploys when users open a product's packaging for the first time. This could also create entertaining three dimensional board game layouts (see Figure 3-7). Kits could be sold to help crafters create emerging images in scrap book pages. LEM business cards would increase interest and be memorable to potential customers.

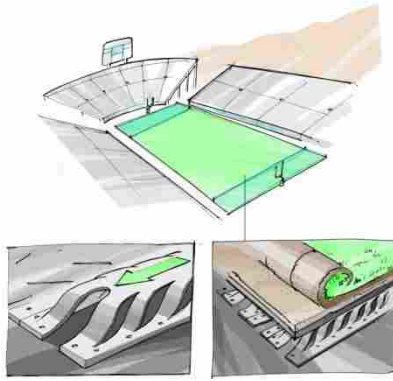


Figure 3-8: Shock Absorbing LEMs that Improve Control Over Spring and Damping Properties

3.5.5 Shock Absorbing

The energy absorption of LEMs can be useful in many shock-absorbing products. Athletic flooring, turf, and footwear with a layer of energy absorbing LEMs could allow more control over spring and damping properties than current padding (see Figure 3-8). This could reduce sports injuries that develop due to repeated impact. Protective armor could be manufactured with multiple layers of energy absorbing and dissipating LEMs, possibly improving upon current bullet-proof technologies [38]. A deploying spring system that encases sensitive electronics could cushion against drops that typically cause damage, and a flexible suspension matrix for crates of produce could also reduce bruising and cracking in the fruit and egg industries. Cushioning LEMs could be stamped into metal seating surfaces to allow a more comfortable distribution of body pressure.

3.5.6 Deployable Mechanisms

Deployable LEMs have many useful applications. Mechanisms and structures with significant empty space are prime candidates to become deployable mechanisms. A deploying desk and chair could eliminate the need for an extra room for a home office, making them more

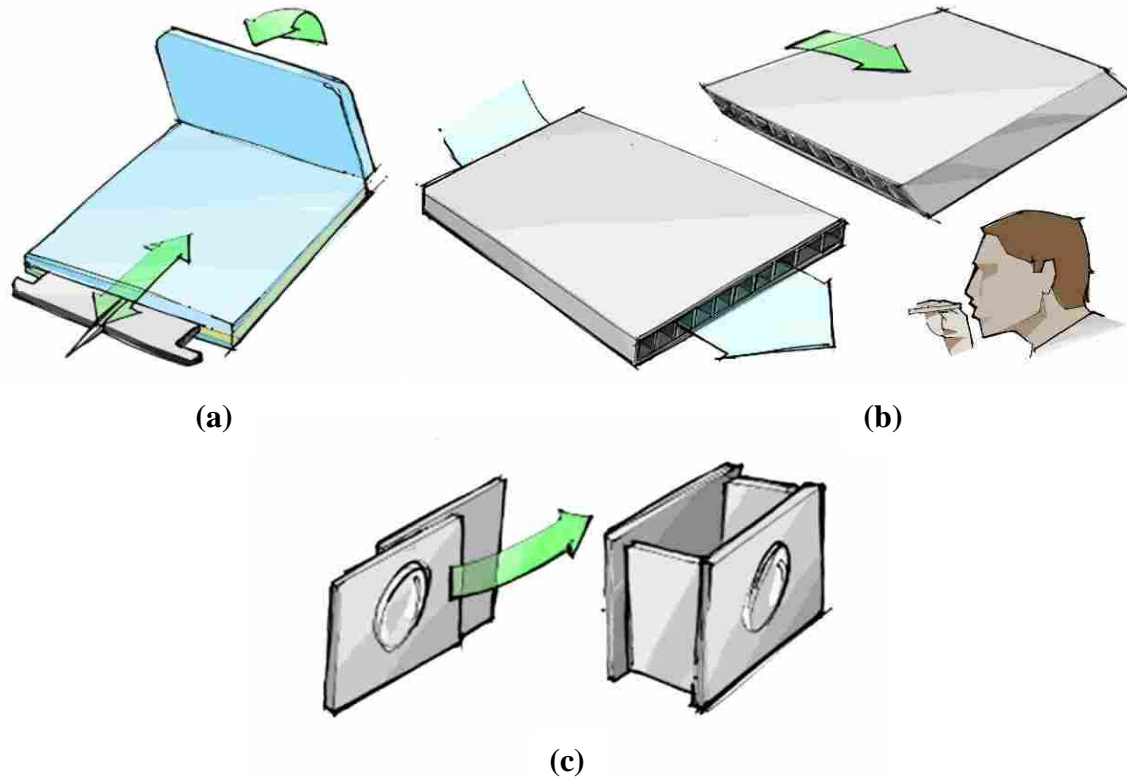


Figure 3-9: Possible Credit-Card-Sized LEMs: (a) Blood Lancet (b) Inhaler or (c) Camera

available to the general population. International barge containers could be collapsed during return transport to reduce the cost associated with shipping empty space. Temporary structures could be LEMs, allowing innovative, deploying camping shelters, green houses, and field medical rooms.

Many deployable devices could be the size of a credit card and easily carried in a wallet for unexpected situations (see Figure 3-9). A compact blood lancet for blood testing would be useful for diabetes patients. Credit card sized adrenaline injectors could be useful for people with serious allergies. A small inhaler could easily be carried by asthma patients for use in case of emergencies. Even a single-exposure, disposable camera could fit inside a wallet in case of unplanned photograph opportunities.

3.6 Conclusions

Each of the LEM opportunities has many potentially viable applications. The credit-card-sized form factor can especially benefit from the unique characteristics of LEMs. Credit-card-sized LEMs can simultaneously maintain a very low profile and an ability to have complex, out-of-plane motion. The following chapter will establish LEMs as a means for expanding the capabilities of credit-card-sized products.

CHAPTER 4 EXPANDING THE CAPABILITIES OF CREDIT-CARD-SIZED MECHANISMS

4.1 Introduction

There is significant motivation for the development of credit-card-sized products capable of various functions. The appeal of these products originates from their unique and universally accepted shape (3.370" x 2.125" x 0.03") [39],[40]. In many respects, the form factor of a credit card epitomizes portability because it can be carried easily in a pocket, wallet, or purse. Products can be designed to exploit this form factor, making them very attractive to consumers.

Many credit-card-sized products have already been pursued. For example, patents exist for pagers [41], magnifying lenses [42], and hair combs [43] that are the size of a credit card, and multiple products already exist in the marketplace. The diversity of these devices attests to the viability of credit-card-sized products, but increased performance capabilities could expand this type of product into new applications.

The incorporation of mechanical features into credit-card-sized products allows for a variety of additional capabilities to be provided. Mechanisms can generate prescribed motion paths, provide reaction forces, or store energy. Products with mechanical features have generally provided movement in the plane of the product. If products could be designed to achieve significant movement out of the plane, then more complex and sophisticated devices could be realized.

The development of credit-card-sized mechanical devices is most challenging due to constraints on thickness. Products could have a slightly larger thickness than an actual credit card and maintain the ability to fit in a wallet, but generally products must have a low profile to be attractive to consumers.

LEMs could be a means of creating high-performance credit-card-sized mechanisms. LEMs are defined as a type of compliant mechanism that is designed to be fabricated from sheet goods (lamina) and has motion that emerges from the plane of fabrication. LEMs could provide credit-card-sized mechanisms with impressive performance by creating large, out-of-plane motions while remaining ultra-thin and compact for storage. This chapter establishes LEMs as a means for expanding the performance of credit-card-sized mechanisms and develops a set of criteria to determine whether a potential product application is a suitable candidate for using LEM technology to create or improve a credit-card-sized product.

4.2 Credit-Card-Sized Mechanisms

Rigid-body mechanisms, in-plane compliant mechanisms, and LEMs can be applied in credit-card-sized products. A brief review of these mechanism classes along with the state-of-the-art in applying each class to credit-card-sized devices is provided as a context for discussing related developments.

4.2.1 Rigid-Body Mechanisms

Traditional, rigid-body mechanisms are composed of rigid links connected at movable joints. These joints, such as revolute joints (hinges) and prismatic joints (sliders), are the mechanisms that are familiar to most designers, so they are very common in mechanical products.

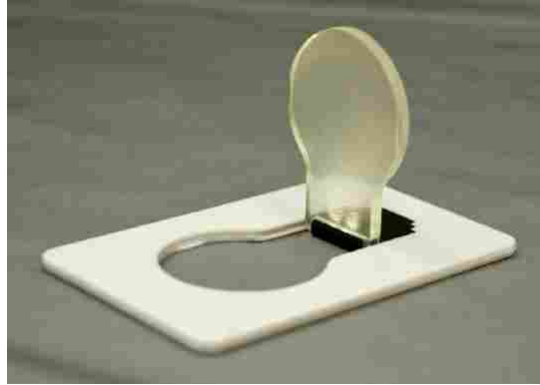


Figure 4-1: Example of a Credit-Card-Sized Rigid-Body Mechanism

Many credit-card-sized products use rigid-body mechanisms to achieve motion. Examples include a dental floss dispenser [44], a sound recording device [45], and a USB flash drive cover [46]. The credit card sized lighting device shown in Figure 4-1 uses a revolute joint to close an LED circuit and position a lens. A great deal of research has been performed regarding the manufacture of mechanisms on this scale [47-50]. The research was motivated by a need to address the challenge of fabricating small devices and attests to the difficulty of developing sophisticated mechanisms that are viable at the credit card size.

4.2.2 In-Plane Compliant Mechanisms

In-plane compliant mechanisms can be defined as compliant mechanisms that are fabricated from sheet materials and whose motion remains in the original manufacturing plane. Much of the work that has been done in compliant mechanisms can be classified as in-plane [51]. For example large-displacement linear-motion mechanisms [52] and compliant overrunning clutches [53] operate in the main plane of the mechanism. Even topology optimization of compliant mechanisms is normally done in two dimensions, so it can also be referred to as in-plane [54],[55].

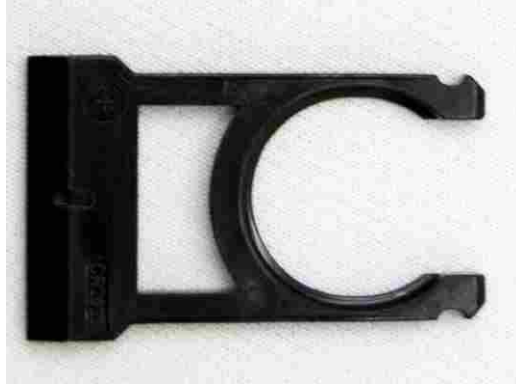


Figure 4-2: Battery Lock as a Credit-Card-Sized In-Plane Compliant Mechanism

Examples of credit-card-sized devices that use in-plane compliant mechanisms to achieve motion include a battery-cover locking mechanism for a handheld remote (see Figure 4-2), a switch for a small lighting device [56], and a flexible casing for a memory card connector [57].

4.2.3 LEMs

As mentioned previously, there has been significant work performed recently to better define and understand LEMs. A framework has been established, outlining basic principles to help in the design and synthesis of LEMs [6], and new joints and flexures that are well-suited for fabrication from sheet materials have been created [11-13]. Work in compliant ortho-planar mechanisms has resulted in a general design process for LEMs, demonstrating the feasibility of using morphing, a change in the number of effective links as a mechanism moves from one configuration to another [18], to enhance LEM capabilities [17].

Few credit-card-sized products have been developed that incorporate mechanisms that could be identified as LEMs. An emerging holder for credit cards [58] and an alarm clock [59] are two examples that have movement out of the plane. Although credit-card-sized devices with mechanisms that meet the definition of LEMs do exist, products that deliberately leverage the

performance advantages of LEMs have apparently not been developed. One notable exception is a deployable, single-use camera, which features a low profile and the capacity to be fabricated from sheet goods [60]. Also, products that could potentially be developed into credit-card-sized LEMs have been identified in Chapter 3. There is an opportunity to use LEMs to expand the capabilities of credit-card-sized products.

4.3 Expanding the Capabilities of Credit-Card-Sized Mechanisms with LEMs

Incorporating mechanisms into the extreme form factor of a credit card is challenging. LEMs can help overcome some of the limitations associated with using rigid-body mechanisms and in-plane compliant mechanisms. Table 4-1 summarizes the challenges of using rigid-body mechanisms and in-plane compliant mechanisms and lists the corresponding LEM advantages.

4.3.1 Challenges with Rigid-Body Mechanisms

Rigid-body mechanisms present some unique challenges when applied to credit-card-sized devices. Two of these are described below.

4.3.1.1 Assembly Required

In rigid-body mechanisms, at least some assembly must be done, unless extra measures are taken so that joints are carefully fabricated in an assembly [61]. Otherwise, assembling small components inside the mechanism can require significant time and dexterity.

Table 4-1: Challenges of Rigid-Body and In-Plane Compliant Mechanisms and Their Respective LEM Advantages

	Challenges	Advantages of LEMs
Rigid-Body Mechanisms	Assembly Required	Reduced Assembly
	Large Thickness	Reduced Thickness
In-Plane Compliant Mechanisms	Limited to Planar Mechanisms	Increased Availability of Mechanisms
	Sensitive to Manufacturing Variations	Reduced Sensitivity to Manufacturing Variations
	Limited to Small Deflections	Increased Deflection Potential
	Limited Stability	Increased Stability
	Limited to Low Forces	Increased Force Potential
	Limited Energy Storage Potential	Increased Energy Storage Potential

4.3.1.2 Large Thickness

Traditional mechanisms usually require that links somehow coincide or overlap at the point of attachment, as illustrated in Figure 4-3. This causes a two-fold increase to overall thickness in the mechanism, which is undesirable for credit-card-sized devices.

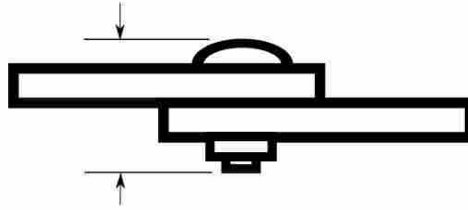


Figure 4-3: An Increase to Overall Thickness Caused by Using Rigid-Body Mechanisms

4.3.2 Challenges with In-Plane Compliant Mechanisms

In-plane compliant mechanisms are sometimes used for credit-card-sized products. The use of compliance helps to overcome the challenges of rigid-body mechanisms by reducing or eliminating assembly and allowing smaller overall mechanism thickness. However, there are some limitations associated with using compliant mechanisms that have in-plane motion.

4.3.2.1 Limited to Planar Mechanisms

By definition, the links of in-plane mechanisms stay within the original plane of the device, so the design is two-dimensional. The output motions are limited to those that can be described with planar kinematics.

4.3.2.2 Sensitive to Manufacturing Variations

The stiffness of a flexure is greatly impacted by the height of the flexure's cross section. The height dimension has a cubic relationship with cantilever beam stiffness

$$\text{Stiffness} = \frac{Ewh^3}{4L^3} \quad (4.1)$$

where E is the modulus of elasticity for the base material, h is beam height, w is beam width, and L is beam length. Physically, the height dimension is determined for in-plane compliant mechanisms when material is removed during manufacture (see Figure 4-4). This makes in-plane

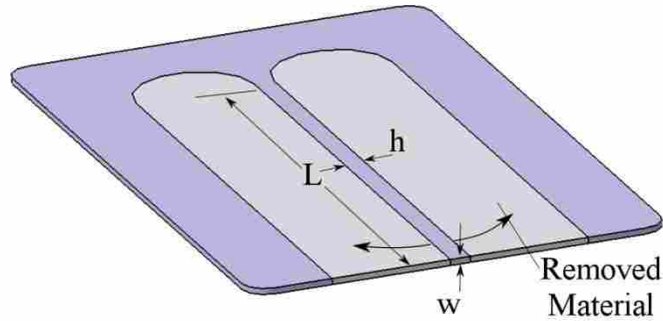


Figure 4-4: An In-Plane Flexure's Height (h) Is Sensitive to Manufacturing Variations.

mechanisms highly sensitive to variations in the size and positioning of fabrication tooling. It is possible to use a manufacturing process that does not depend on material removal, such as injection molding; however, this generally removes the cost advantages inherent to planar manufacturing.

4.3.2.3 Limited to Small Deflections

According to Eqn. (2), the maximum deflection of a cantilever flexure is another performance parameter that is affected by the height of a flexure's cross section

$$\delta_{\max} = \frac{2\sigma_y L^2}{3Eh} \quad (4.2)$$

where σ_y is the yield strength of the base material [3]. Due to vibration and deflection of these members during milling, shearing constraints during stamping, or heat transfer during laser cutting, there are limitations to the minimum obtainable height of a flexure for in-plane compliant mechanisms [62]. An increase to the height of the cross section leads to a smaller allowable deflection in the beam.

Alternatively, a higher precision manufacturing process could be used to create flexures with a smaller height dimension, but they can be much more expensive for mass production.

4.3.2.4 Limited Stability

Because of the manufacturing constraints described above, the height of the cross section of a flexure is often much greater than the width. Such a cross section is said to have a high aspect ratio

$$\text{Aspect Ratio} = \frac{h}{w} \quad (4.3)$$

giving the beam poor off-axis stiffness. These beams can have significant problems with lateral torsional buckling, causing undesired motions where the beam exits the plane of the mechanism [63].

One possible solution for instability in credit-card-sized in-plane mechanisms is to add additional layers to constrain the mechanism's motion in the plane, but this likely adds undesired thickness to the mechanism.

4.3.2.5 Limited to Low Forces

According to Eqn. (1), another factor in the stiffness of a flexure is the width of the cross section. This dimension refers to the thickness of a layer for in-plane credit-card-sized mechanisms. It is common in compliant mechanism design to simply increase the width of a flexure's cross section to increase the force because this will not affect the stress in the beam for a given deflection [3]. However, to maintain the portability and convenience of the device, minimizing thickness is important. Thus in-plane compliant mechanisms are generally limited to low forces for credit-card-sized mechanisms.

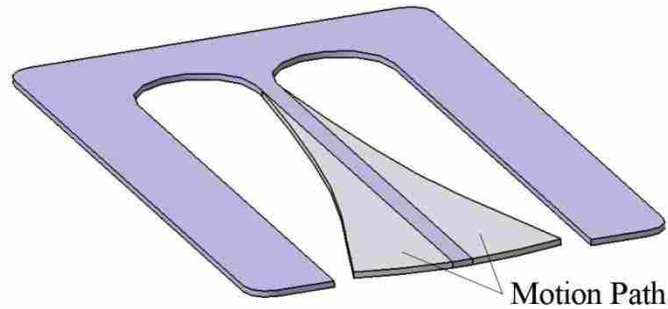


Figure 4-5: Material Removed From In-Plane Motion Paths Reduces Energy Storage Potential

4.3.2.6 Limited Energy Storage Potential

The function of in-plane compliant mechanisms relies upon the removal of material from the motion path of the mechanism (see Figure 4-5). This reduces the total amount of material available to place in strain for storing mechanical energy in credit-card-sized devices.

4.3.3 Advantages of LEMs

Each of the described challenges of using rigid-body mechanisms or in-plane compliant mechanisms can be avoided by using LEMs.

4.3.3.1 Reduced Assembly

In LEMs, often each layer or the entire mechanism is monolithic, meaning it is made of only one piece. This can reduce or even eliminate the need for tedious assembly of small components in credit-card-sized mechanisms.

4.3.3.2 Reduced Thickness

Unlike traditional, rigid-body mechanisms, LEMs do not require linkage of joints for motion, so there is no need for links that coincide or overlap at the point of attachment, which

necessitate unwanted thickness increases. The thickness of the mechanism can be as small as the nominal thickness of the base compliant material.

4.3.3.3 Increased Availability of Mechanisms

Because the kinematics of LEMs are not constrained to a plane, designers have many more mechanisms available for use. Credit-card-sized LEMs could contain mechanisms that are planar, spherical, cylindrical, or spatial. An appeal of LEMs is their ability to have motion that is orthogonal to the plane of manufacture. The introduction of a third dimension of motion creates significant opportunities for credit-card-sized mechanisms.

4.3.3.4 Reduced Sensitivity to Manufacturing Variations

The material that is removed during the manufacture of LEMs only affects the width of the flexure's cross section. This has a smaller effect on the stiffness of flexures than the height, so credit-card-sized LEMs are much less sensitive to variations in the size and positioning of fabrication tooling than in-plane compliant mechanisms. This provides designers with a larger selection of usable manufacturing processes.

The height of a flexure's cross section in LEMs is determined by the thickness of the material that the mechanism is made from. Variations in sheet thickness are normally very small and are much less expensive to control than variations in material removal.

4.3.3.5 Increased Deflection Potential

Since a decreased height in a flexure's cross section allows for an increased maximum deflection, LEMs are an excellent candidate for increasing motion in credit-card-sized mechanisms. A mechanism could have large deflections and still be thin and portable.

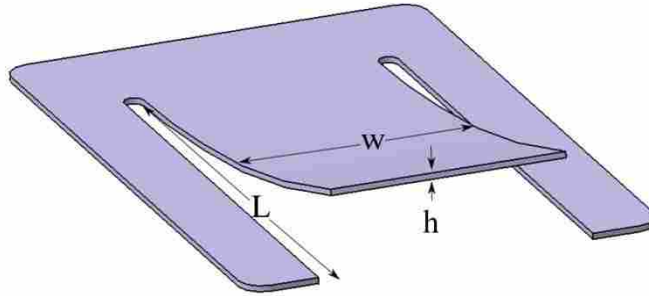


Figure 4-6: Increased Material Available for Energy Storage Potential in LEMs

4.3.3.6 Increased Stability

Using LEMs for credit-card-sized mechanisms helps to avoid undesired motions. The width of a LEM flexure will normally be much greater than the thickness of the material, so cross sections have a desirable aspect ratio. This improves the off-axis stiffness of flexures and eliminates problems with lateral torsional buckling. Additional layers are not needed to constrain the mechanism's motion; this facilitates the creation of mechanisms that have a small thickness.

4.3.3.7 Increased Force Potential

To increase reaction forces, LEMs can have wide flexures. Unlike in-plane mechanisms, this does not require an overall increase in the thickness because flexure width is a dimension within the plane of the mechanism.

4.3.3.8 Increased Energy Storage Potential

The out-of-plane motion of LEMs does not require any material to be removed from the motion path of the mechanism. Thus a larger footprint of base material is available for the storage of strain energy (see Figure 4-6).

4.4 Suitability Criteria

Understanding the advantages of using LEMs for credit-card-sized products can motivate designers to create new products. Therefore, it is useful to develop criteria for determining if a product is a suitable candidate for using LEM technology to create a credit-card-sized product. These criteria could also be used to determine whether an existing credit-card-sized product would benefit from using LEM technology. The evaluation criteria are developed directly from the list of eight advantages of LEMs over rigid-body and in-plane compliant mechanisms discussed previously.

4.4.1 Baseline Criteria

For a product to be a candidate for using LEM technology to become a credit-card-sized device, some baseline criteria must be met. A product that meets all three of the baseline suitability criteria is a candidate for using LEM technology for a credit-card-sized product. If a product does not meet one of the baseline criteria, then it is not likely a viable candidate for becoming a LEM credit-card-sized product.

Four of the advantages of credit-card-sized LEMs from Table 4-1 would be beneficial for almost any credit-card-sized product. These advantages are: reduced assembly, reduced thickness, reduced sensitivity to manufacturing variations, and increased stability. If a product meets the baseline criteria for becoming a credit-card-sized LEM, it will likely benefit from all four of these advantages. Descriptions for each of the baseline criteria follow.

4.4.1.1 Mechanical Function

For LEM technology to add value, a product must have some mechanical motion, either during initial manufacturing and assembly or during product use.

4.4.1.2 Portability

The best candidates for credit-card-sized products are those which consumers will want to keep with them. This includes products that would benefit from compactness, low profiles, or portability. If portability of a product is not valuable to consumers, then it is not likely a strong candidate for becoming a credit-card-sized mechanism.

4.4.1.3 Small Volume

Products that can have a small volume are best for credit-card-sized mechanisms. Products that require large volumes for basic function, such as water storage, are not likely candidates for credit-card-sized mechanisms.

4.4.2 Special Criteria

Of the eight advantages of credit-card-sized LEMs in Table 4-1, four advantages may only be useful in certain product applications. These advantages compose the three special criteria. Potential applications that meet any of these special criteria in addition to all of the basic criteria are especially suitable for LEMs. The special criteria are described below.

4.4.2.1 Complex Motion

LEMes have an ability to create complex motions because they move out of the fabrication plane. For instance, spherical, cylindrical, and spatial mechanisms can be created. Products that require complex motion can be especially suitable for credit-card-sized LEMs.

4.4.2.2 Large Deflections

As described previously, products that require large out-of-plane deflections could be suitable for becoming credit-card-sized LEMs. Even devices that typically have in-plane deflection might be oriented differently to deflect out of plane, allowing designers to utilize the increased deflection capability of LEMs to create credit-card-sized products.

4.4.2.3 Energy Storage

Storing significant strain energy through mechanical deformation can be challenging in the credit card form factor. However, this could be useful in products that require energy storage or prescribe large forces. These products may be especially suitable candidates for using LEMs because of the LEM advantages of increased force potential and energy storage potential.

4.5 Conclusions

The literature review in this chapter reveals that significant previous work has been done in rigid-body mechanisms and in-plane compliant mechanisms to allow the development of credit-card-sized products. Also, many products and patents exist for credit-card-sized products. That work is evidence that credit-card-sized products can be an attractive area for product development.

LEMes have many advantages over rigid-body and in-plane compliant mechanisms, and they could be a means for expanding the capabilities of credit-card-sized products. Criteria have been developed for evaluating the suitability of a potential product for using LEMs to create or improve a credit-card-sized product. These criteria are based on the eight advantages of LEMs over rigid-body and in-plane compliant mechanisms.

CHAPTER 5 EXAMPLE LEM APPLICATION

5.1 Introduction

A LEM credit-card-sized lancing device has been developed to illustrate the expanded capabilities described previously. The device could be a major component for a credit-card-sized syringe. This product would be convenient for carrying and delivering prescription drugs that are needed in emergency situations. One potential use could be to inject epinephrine during anaphylactic shock, a potentially lethal allergic reaction. A current product that delivers epinephrine is the EpiPen®.

An EpiPen® has 2 cc of prescription fluid, with a typical dose of only 0.3 cc [64]. The current EpiPen® is about 16 cm long in its carrier tube with a volume around 70 cc; thus the actual dose of epinephrine is about 0.4% of the total volume of the device. An EpiPen® is meant to be carried at all times yet can be cumbersome. There is motivation for a more convenient device that can perform the same drug delivery function. This may be an ideal candidate for a credit-card-sized LEM.

5.2 Suitability Criteria

According to the suitability criteria from the previous chapter, this device is an excellent candidate for a credit-card-sized LEM. The product has mechanical function, requires portability, and could have a very small volume. In addition, the product requires complex motions, large deflections, and energy storage.

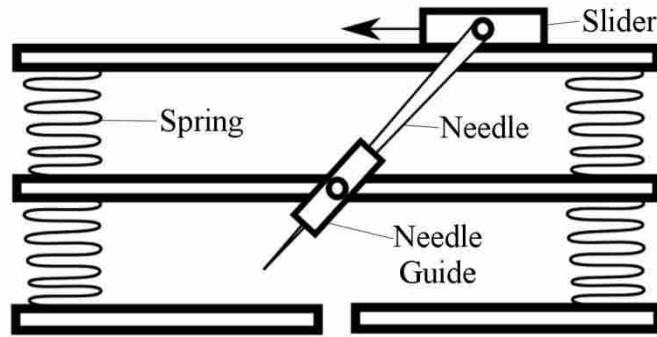


Figure 5-1: Conceptual Design for the Credit-Card-Sized Lancing Device

5.3 Previous Work

Others have pursued credit-card-sized injector designs; however, none of these ideas are embodied in products found on the market today. These devices generally depend on rigid-body mechanisms for their motion. One patent uses a gear train for injection [65]. Another uses a series of rigid-bodies and coil springs to lance the needle, which dramatically increases the thickness of the device [66]. Two [67],[68] have small LEM components, but would benefit from applying LEM principles to obtain larger deflections.

5.4 Design Description

At a conceptual level, the device is designed to allow for orthogonal lancing motion and flat storage. It consists of three main layers separated by springs as illustrated in Figure 5-1. The bottom layer is a stable base to be pressed against the leg of a patient. The middle layer is a guide for the needle to pass through, made up of an inverted slider mounted on a revolute hinge. The top layer contains the needle mounted to a slider on a revolute hinge.

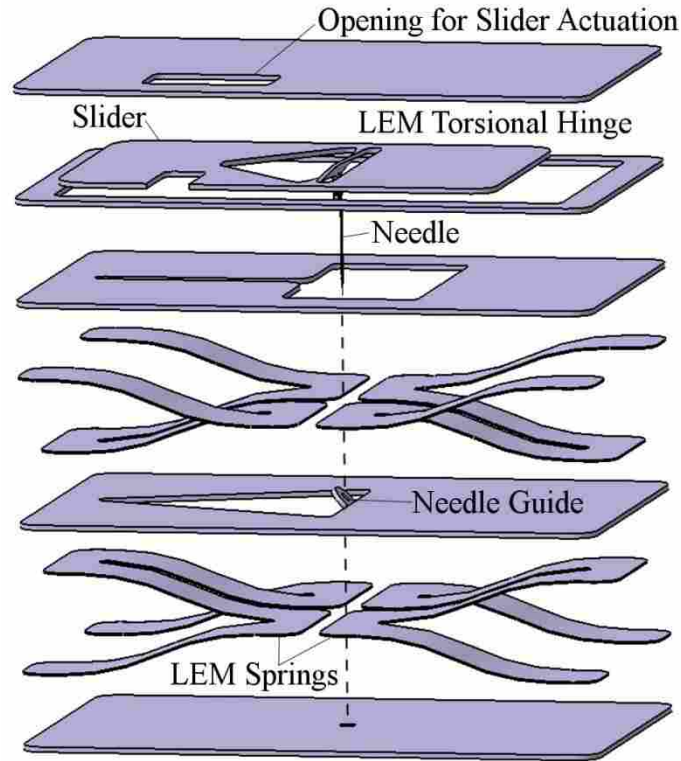


Figure 5-2: Exploded View of the Credit-Card-Sized Lancing Device

An exploded view of the embodiment is shown in Figure 5-2. The first layer in the design is a base plate with a hole for the needle to pass through. The second layer consists of two symmetrical folded-beam springs. The third layer contains a small piece of material bent at 45 degrees with a hole through it. This is used to guide the needle while accommodating its rotation and translation (see Figure 5-3). Next is another layer of LEM folded-beam springs. The fifth layer is the lower containment for the slider. The sixth layer is a slider with the needle mounted on a LEM torsional hinge to allow rotation (see Figure 5-4). The top layer features an opening where the user can actuate the slider. Figure 5-5 demonstrates the ability for the device to be stamped from sheet metal.

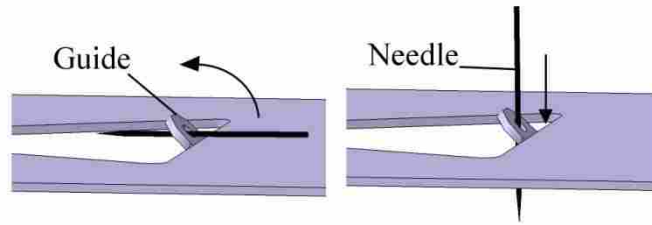


Figure 5-3: Detailed View of the Needle Guide

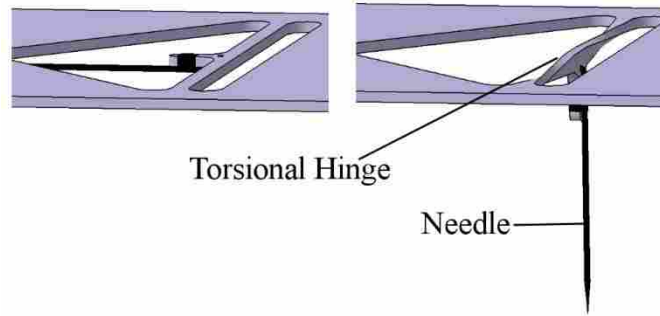


Figure 5-4: Detailed View of the LEM Torsional Hinge

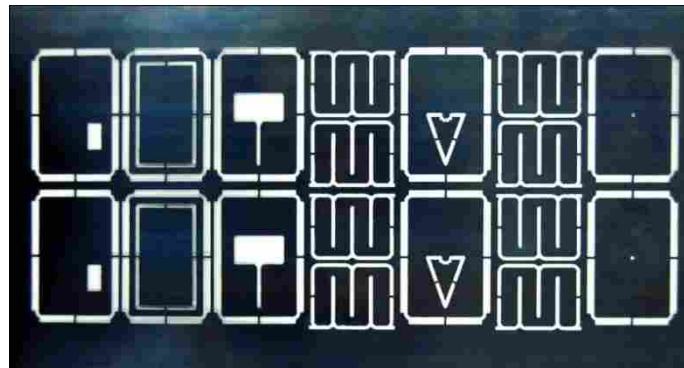


Figure 5-5: Parts for the Credit-Card-Sized Lancing Device Stamped from Sheet Metal

5.5 Stress Analysis

The LEM folded beam springs used in the device have constant curvature. This simplifies the stress analysis because when all of the curved sections of the beam are flattened for storage, they will have the same bending stress. Beams with constant curvature can use

$$\sigma_{\text{Bending}} = \frac{Eh}{2R} \quad (5.1)$$

to determine bending stress [69]. In this case, h is the thickness of the lamina (0.01”), R is the initial radius of curvature (1.875”), and E is the elastic modulus of elasticity for steel (30E3 ksi). Thus the bending stress in the beam is 80 ksi, which is well below the yield strength of a blue-tempered spring steel. Note that this analysis relates to the flattened state of the spring, and there may be higher bending stresses in some mode shapes while the spring is being flattened. Also note that this equation is normally used for induced curvature in flat beams rather than induced flatness in curved beams.

5.6 Operation

The device is stored in the flattened form, so it can be carried in a wallet or purse (see Figure 5-6). When the device is removed from the packaging, the LEM folded beam springs push the mechanism open (see Figure 5-7). This permits the motion of the mechanism, and initiates the rotation of the needle. By using the opening in the top layer, the slider is moved until the needle is fully rotated into place (see Figure 5-8). Finally, the user places the device on a thigh and pushes on the top of the mechanism to lance the needle (see Figure 5-9).



Figure 5-6: Lancing Device Being Removed from a Wallet

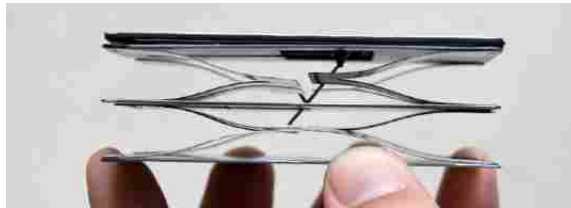


Figure 5-7: Expanded Lancing Device after Removing from Packaging

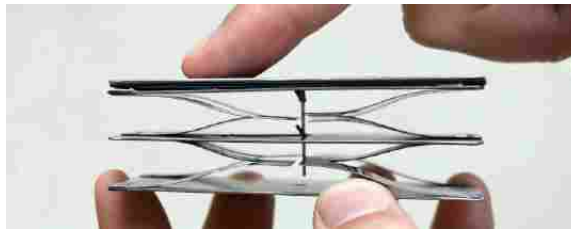


Figure 5-8: Needle Being Manually Rotated into Place Using the Slider Mechanism



Figure 5-9: Needle Being Lanced into a Patient's Thigh

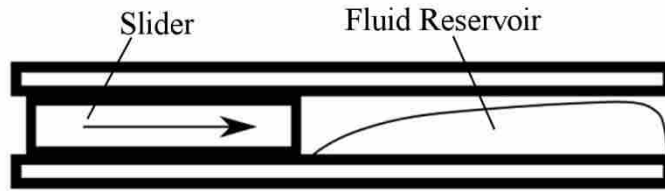


Figure 5-10: Concept for a Low-Profile, Peristaltic, Fluid-Dispensing System

5.7 Benefits from LEMs

The design of the lancing device exemplifies many of the advantages of using LEMs in credit-card-sized mechanisms. The design has twelve parts, which is fewer than any of the referenced patents or Epipen®. There is no increase in thickness from the joining of rigid links, so the mechanism maintains a low profile. The total thickness of the device when it is stored flat is 0.12"; this represents an 80% decrease in the volume of the device when compared to the Epipen®. The mechanism uses orthogonal motion, which would have been unavailable if in-plane compliant mechanisms were used. Finally, the LEM folded beam springs feature reduced sensitivity to manufacturing variations and increased deflections, stability, reaction forces, and energy storage.

5.8 Fluid System

Although not part of this paper, some preliminary concepts have been explored for a low-profile fluid dispenser. One concept uses a peristaltic motion to inject the fluid (see Figure 5-10). By placing a fluid reservoir in a layer with a plunger, the typical 2 cc of prescription fluid could be contained in a 1.5" X 2" layer that is only 0.04" thick, allowing the device to maintain a low profile for wallet storage.

5.9 Conclusions

The lancing device uses many of the advantages of LEMs to improved the performance over the current EpiPen®. It maintains a low profile, while featuring large out-of-plane deflections. The device satisfies the suitability criteria and exemplifies many of the expanded capabilities of LEMs over rigid-body mechanisms and in-plane compliant mechanisms for credit-card-sized products.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research has shown that LEM technology has many advantages and that previous research has developed design tools to overcome many LEM design challenges; the technology is prepared for product implementation. Technology push product development processes have been used to identify potential applications for LEMs. Opportunities for six classes of products are enabled by LEM advantages, namely disposable LEMs, novel arrays of LEMs, scaled LEMs, LEMs with surprising motion, shock absorbing LEMs, and deployable LEMs. Numerous potential applications for LEMs have been discussed for each of these opportunities. These applications reveal the breadth of potential for products that can benefit from the unique characteristics of LEMs.

Deployable LEMs, particularly in the form factor of a credit card, are an excellent utilization of LEM technology. This is due to the ability of LEMs to have a low profile yet generate large, sophisticated motions out of the plane of the mechanism. They also present many manufacturing advantages over rigid-link mechanisms and in-plane compliant mechanisms. These LEM advantages can greatly expand the capabilities and improve the performance of credit-card-sized mechanisms. This has been demonstrated in the design and prototyping of the credit-card-sized lancing device.

6.2 Recommendations

There are many opportunities for further research, and their pursuit is recommended. In this thesis, only the expanded capabilities of credit-card-sized mechanisms have been investigated, but other opportunities that are enabled by LEMs have been discovered. Some of the product applications identified require competencies in other areas for successful development. Future research involves investigation of these areas, perhaps collaborating with other research groups to overcome design challenges. Note that a detailed search of prior art related to LEM applications, distinguishing between novel concepts and existing patents, should be performed prior to commercial pursuit of any application. Novel concepts can be exploited for implementation into marketable products.

Future work also involves more research into mechanical devices that could be the size of a credit card. Some have already been identified in this work, but the expanded capabilities of credit-card-sized mechanisms merit a deeper investigation into possible compact applications. A second LEM workshop, modified towards identifying credit-card-sized or low-profile products, may yield substantial results.

Finally, further development of the credit-card-sized lancing device could lead to a marketable product. Research could focus on sterile storage and use, reliable fluid dispensing, and robust mounting of the needle. Contacting corporate sponsors could lead to further insight and a better understanding of customer needs and health regulations. Finite element analysis could be performed on the lancing device to predict bending stresses more accurately.

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APPENDIX A: LEM WORKSHOP GUEST LIST

Name	Background or Affiliation	Sept. 15	Sept. 18
Nathan Albrechtsen	Brigham Young University	✓	✓
Larry Howell	Brigham Young University	✓	✓
Spencer Magleby	Brigham Young University	✓	✓
Gregg Bishop	Technology Push Product Development	✓	
Mark Crawford	Director of Medical Product Development	✓	
Michael Horito	Industrial Design		✓
Richard Fry	Industrial Design	✓	
Ken Hardman	Boeing	✓	
Bryan Dunford	Industrial Designer		✓
Dee Anderson	Office of Technology Transfer		✓
Scott Lyon	L3 Communications		✓
Susan Bromley	Microelectromechanical Systems	✓	
Brett Brimhall	IM Flash		✓
Jason Richardson	Entrepreneur	✓	
Tom Johnson	L3 Communications, GE, Boeing, 3Com		✓
Louis Eubank	Lead user in outdoor gear		✓
Amy Brennan	Economic Center for Self-Reliance	✓	
Joan Dixon	Economic Center for Self-Reliance	✓	
Aaron Smith	Patent Attorney, Symantec Corporation	✓	
Jeff Lillywhite	Patent Attorney		✓

APPENDIX B: LEM APPLICATION IDENTIFICATION

Complex Motion

- Booby Traps/ Security Systems
- Long-Range Grippers
- Interrogation Devices
- Blender (Expansion Caused By Electrical Current, Increases Volume)
- Deployable Wallet
- 1 Piece Syringe
- De-Icing Surfaces (Salt Cleaning)
- LEM TV, Theaters, Sporting Events
- Morph Aesthetics - Match Mood/ Status (Car Wheel Spinners, Jewelry, Car Exterior, Hair Brush, iPod)
- Pop-Up Safety Shield Upon Equipment Failure
- Looms (Microcredit)
- Cheaper Farming Combines
- House Painting Robot
- Robot Surgery (Prescribed Motion)
- Patient Exercise
- Hygiene Kits
- Snake Arms
- Have LEM Robots On Assembly Lines
- Multi-Position Switches
- Small (MEMS?) Switches To Replace Pin Rows On Printed Circuit Boards
- Medical Tray To Hold And Present Instruments
- Multi-State Pc Bits

- Screen Doors With No Hinge Or Shock (Opens To Any Position)
- Blood Sampler (Layered LEM)
- Deployable Keyboard Straight From PCB
- Rotating Sign
- Switch Ink Color In A Pen
- Medical Devices - Finger Prick For Blood Typing
- Wafer Handling Robot
- Integrated Blood Sampling Device

Cushioning

- Shoes
- Seat Cover
- Cot – Spring System
- Disposable Spring Systems - Couches, Beds, Chairs
- Slide In Springs For Shoes

Deployable Space

- Compartments
- Containers
- Deployable Storage Boxes

Energy

- Seat Cushion
- Arrays - Beds
- Arrays - Seats
- Cot - Legs That Unfold To Allow A Level Plane On Rough Terrain
- Office Chair Mechanism With Adjustable Tension

Or Pressure In Seat Or In Joints

- Hybrid Car
- Wind/ Wave Power
- Road Compression
- Auto Shocks
- Generating Electricity From People Walking
- Energy Stuff In Glovebox
- Energy Storage (One-Time Release)
- One-Time Use Energy Deployment (Cutting?)
- Shoes
- Skiboats
- Shock Absorbing Car Bumpers
- Shock Absorbing Athletic Floors
- Jumping Bag For Actors To Fall Onto
- Compliant Buildings To Dampen
- Armor
- Protective Cases
- Kids Uniform
- Suspension
- Arrays - Carpet Padding
- Umpire Protection
- Treadmill Bed
- Gas Assist Shock (Hatchback That Is Not Temperature Dependent)

Entertaining Motion

- Decorating Lawn Ornament
- Disposable - Hats
- A Toy In A Birthday Card

- Mechanical Learning Kits For 3rd World Countries
- Cereal Boxes
- Morphing Toys
- Morphing Stage In A Play
- Wow Visual Aids
- Interactive Board Games
- Pop-Up Scrap Books
- Candy
- Costumes
- Loose Diamond Case To Store Then Deploy And Display
- Pop-Up Business Cards
- Collapsible Toys
- Prank Toys
- Pop-Up Health Education
- PopUp Moneywise Literature
- Toys
- Surprising Motion
- Science Fair Displays
- Low Cost Costumes
- Transformer Toys
- Deployable Christmas Decorations
- Third World Teaching Materials
- Third World Educational Items
- LEM Toys - Star Wars Assembly Set
- Bakugan - Toy Automatically Changes With Magnets
- Visuals Aids For Teaching
- LEM Kit Where You Can Pop Out And Stack

Fluids

- Fins
- Surface Texture For Drag Or Braking
- Low Cost Air Filters With LEM Indicators
- Disposable - Fans
- Irrigation System That Opens And Closes Cheap Valves To Let Water Flow To Specific Points
- Change Surface Texture/ Roughness/ Reflectivity
- Fluid Pumping Pipes
- Pumps
- Braking
- Fan
- Surface Braking
- Third World Piping Systems
- Third World Running Water
- Slow Down After Launch
- Variable Orifice Filters
- Variable Orifice Venting (A/C Or Under Hood Of Car)
- Vents That Return To Planar State For Cleaning
- Windows That Pop-Out For Ventilation
- Membrane Filters
- Purification
- Array Flat Filter
- Membrane Filters
- LEM Filters
- Ventilation
- Glass: Morphing Window
- Air Diffuser
- Self Adjusting Roof Vents

Force

- Haptic Interfaces With Tiny LEM Arrays
- Scales
- Pen Spring
- Spring Boards (Gymnastics)
- Flat Spring For Pressure Valve
- Flat Spring For Electrical Contacts
- Coil Spring (Stamp Flat Springs And Pull Up)
- Lifting Mechanism/ Jack (Motorcycle Or Lifting Boxes)
- Adjustable Tension Springs
- Portable Jacks For Earthquakes
- Weigh Station
- Arrays - Adjustable Springs
- Scales
- Force Open Narrow Spaces
- Flat Spring For Battery Contacts

Light

- Light Aperture Array Over Pixel Array Or Other Frequency
- Variable Aperture Lighting For Art Displays/ Cool Effects
- RF Absorption Metering
- Glass: Morphing Side Panel
- Novelty (Moving Glass)
- Glass: Morphing Mirror
- Matrix Light Switch Fiber Optic
- Sun Following Motion
- Solar Panels

- Solar Arrays
- Pointing Solar Arrays
- Solar Tracking
- Radio Frequency - Light
- Mirror Arrays
- Arrays - Awnings - Shades
- Glasses
- Compact Binoculars With Drop Down Ratcheting Lock To Adjust Focus
- Glasses Frames
- Articulating Shades
- Disposable - Glasses
- Arrays - Glass - Shading (Windows?)
- One Piece Blinds
- Environmental Uses – Shudders

Micro Scale

- MEMS (Nano Injection)
- Microinjector For Drug Delivery
- Pollution Retaining LEMs
- Internal Diabetes Blood Sample Testing
- Micro Scrub Brush For Clogged Arteries
- Drug Delivery And Sampling
- MEMS To Capture CO₂
- Micro Eaters/ Biters/ Stomers For Clogged Arteries
- Clandestine Sensors
- Pinchless Hinge
- Flex PCBs
- Speakers
- Switchable Velcro
- Traffic Signs That Are Changeable/ Hidden/ Compact/ Multiple Signs

- Toys - Pinchless Hinge
- Foot Articulation Flexibility
- Replace Multiple PCBs
- Planar Speakers - Surround Sound - The Walls Are Speakers
- Speakers In Headphones
- Low-Profile Deploy Onsite Antenna Or Camera
- Tip Sensitive Thermocouple

Shock Absorption

- Protective Cases For Electronics
- Shock Absorber
- Gymnastics
- Body Armor
- Pack Harness Suspension
- Automotive Shocks
- Arrays - Gym Mats
- Cargo Box Suspensions
- Floor Mat
- Custom Orthotics

Simple Motion

- Tweezers
- Scissors
- Hair Brushes
- Clothespins
- Safety Pins
- Prosthetics
- Disposable Tools
- Doors, Windows
- Bands On The Road
- Medical Forceps
- Disposable Kitchen Tongs
- Disposable Nail Clippers
- Garage Doors
- Manholes

- Credit Card Sized Drawing Compass
- Arm
- Hand
- Leg
- Spine
- Medical Joints/Limbs

Transportation

- Bikes
- Patient Moving
- Carry People
- Carrying Devices With Wheels
- Third World Mobility For Disabilities
- Wheelchairs
- Wheel Chairs
- Third World PWDs

Wave

- Pointing Antenna Arrays
- Reflection/ Diffraction/ Recombination Waves Or Signal
- Phase Change - Adding Waves
- Variable Screens Diverter For Stealth
- Audio Screen
- Stealth

Deployable Space

- Portable Garden
- Wells
- Compact Storage
- Tupperware
- Rooms
- Fridges
- Exercise Equipment
- Collapsible Fluid Storage
- Customizable Storage
- Drink Holder
- Drying Rack

- Compact Stove
- Charcoal Box
- Collapsible Shelf Where Additional Shelves Can Pop Out
- Deployable Toaster Or Any Heating Appliance
- A Car That Collapses To Eliminate Empty Space When Not In Use
- Truck Bed That Converts To A Van
- Soccer Goals/ Morphing Playing Fields

Furniture

- Collapsible Workbench Or Seats (Expandable Work Tables)
- Intake Tables In Backpack
- Footbed
- A Table That Folds/ Rolls Up Like A Blanket
- Third World School Kit Where Case Becomes The Desk, Then Switch Back With Carrying Strap
- Chairs
- Tables
- Beds
- Cribs
- Hospital Gurney
- FEMA Emergency Cots & Seats
- Disposable Stadium Seating
- Multi-Use Furniture
- Fold-Out Dental Chairs
- Travelling Desk
- Seating
- Furniture
- Gurnee
- Desks

- Sporting Events - Seating
- Pack Chairs And Tables
- Frame - Converts To Chair/ Bed
- Folding Tables And Chairs
- Furniture
- Medical Bedding
- Emergency Cots In Hospital
- Cot - Made Of Linking Plates
- Seat
- Disposable Desk
- Wooden Folding Chair With No Parts
- Folding Chair
- Third World Portable, Deployable Medical Beds
- Low End Furniture (Tables)
- Table - Couch - Bed Combo
- Bleachers
- Chairs
- Foldout Bed From Walls
- Multi-Modal Furniture

Packaging

- Expandable Semis
- Collapsible Shipping Containers (The Huge Ones)
- Integrated Packaging
- Air Pocket (Shipment Padding Where The Air Can Be Removed)
- Eggs Carton
- Fruit Packaging
- Vials
- Laptop Boxes
- Egg Carton
- Hold ICs In Place For Shipping

- Boxes
- Custom Expandable Packaging
- Easy Open Packaging
- Reusable Packaging
- Low Cost Packaging
- Reduced Weight/Volume Shipping
- Disposable Packaging (In Lieu Of Bubble Wrap)
- Food Packaging - Ready To Eat
- Egg Carton
- Electrical Component Shipping
- Packaging For IC Components

Shape

- Road Work Cones And Barrels
- Chicken Pens
- Huge Solar Shield In Outer Space
- Deployable Splints And Prosthetics
- Emergency Cones For Glove Box
- Safety Cones
- Expandable Casts
- Road Barricades
- Adjustable Shape Bio-Braces

Shelter

- Pop Up Houses
- Emergency Shelter
- Shelter From Bugs
- Portable Medical Room
- Dog Houses
- Prefab Buildings
- Third World Deployable Schools

- Tent - Carrying Platform Or Trailer For Car
- Strengthen Existing Shacks With LEMs
- Tents
- Emergency Shelters
- Popup Tent Covered In Nylon
- Pop-Up Tent
- Tent Structures
- Shelter For Relief After Natural Disasters

Simple Structure

- Gardening Tools
- Kitchenware
- Camping Cookware
- LEM Arrays To Detonate From A Distance
- Disposable - Light (Flashlight) Money
- Disposable - Brush Or Comb
- Arrays Of Blades To Protect While Shipping
- Actuated Toothbrush
- Cheap Farming Tools
- Flights (Travel Dishes)
- Housewares - Compact Utensils
- Disposable - Plasticware - Spatula
- Disposable Paper Cup That Collapses Or Expands
- Disposable Fold Out Paper Plate For Backpacking
- Dishes
- Silverware

Thermal

- Insulation That Becomes Heat Fins
- Clothing (Insulation)
- Adjustable Heat Sinks
- Arrays - Insulation
- Reduce Surface Area To Reduce Heat Loss

Weight-Supporting Structure

- Capes (Batman)
- Street Market Shops
- Cell Phone Towers
- Crutches
- Deployable Fence
- Barricade
- Catheter/ Stent
- Scaffolding
- Bath Tub
- Tripod
- Construction Materials That Are Currently Thrown Out
- Collapsible Camp Toilet
- Climbing Cams
- Folding Kayaks
- Saw Horses
- 2x4
- Trade Show Display Structures
- Fasteners
- Deployable Concert Stage Equipment
- Disposable Backpacks
- Deployable Bridge/ Overpass/ Road Structures/ Rebar
- Tooling Support Structure
- Tripod
- Fences For Animal Enclosure
- Stents
- Bridges

- Drywall Anchor
- Disposable - Stage - Concert
- Disposable Construction Braces
- Stents That Are Releasable
- Third World Crutches
- Structural Support In Arteries

Considerations

- LEM Mfg Jobs
- Incremental Capitalization
- Kits For LEM At Home Mfg
- Completely Adaptable Sizing
- Beyond Pop Ups And Origami
- Variable Height
- Water Proof
- Planar Device To Be Made In 3rd World And Exported
- Adjustable Height Furniture
- Normally Opened Or Normally Closed Arrays

Materials

- Recyclable Materials
- Organic LEMs
- Disposable Materials
- Nitrogen-Based LEMs That Plow And Break Up In The Ground
- Microwavable
- Materials - Plywood
- Materials - Bamboo
- Materials - Wicker
- Materials - Drywall (Gypsum)
- Materials - Glass

- Materials - Rubber
- Third World Materials - Plastic
- Plywood From Compressed Sorghum Stalks
- Third World Materials - Compressed Plywood
- Third World Materials – Glass

Other

- Devices – Light Compact, Complex Motion, No Friction
- Grain Processing Tools
- Contraceptives
- Sterility Devices
- Bombs
- Devices From Sheets
- Less Mfg Scrap
- Pumping Ground Water
- Make Cheaper Products
- Air Seal - Home Energy Efficiency
- Minimally Invasive Surgery
- Oil Drilling Devices For In-Hole Tasks
- Deployable First Aid
- IUD
- Separation Of Materials
- Waste Disposal
- Home Power Generator
- Cover The World With LEMs
- Ice Growing Structures

- Area For Ice Caps To Consolidate On
- Cheaper Mfg
- Faster Assembly
- Reduce Part Count
- Print Money
- Smaller
- Rugged
- Big Toy Jumpstations
- Airkiss
- Deodorant
- Space Exploration
- Outdoor Red-Emergency Prep
- Transportation
- Medical
- Cookware - Mular
- Lighting
- Packaging
- Temporary Use Products
- FEMA
- Medical
- Outdoor
- Resizable, Customizable Devices
- Housewares
- Camping
- Horn
- Third World Headgear
- Furniture
- Third World Exports
- LEM Gate-Array
- Medical Tools
- Cell Phones
- Suction Cup Hangers Instead Of 3m Disposable Ones
- Animal Medical Devices

- MEMS Sensors
- Compact Aircraft (“Plane In A Tube”) Surveillance
- Cars
- Disposable Clothing
- Travel - Luggage
- Steering
- Actuators
- Printers
- Sports Equipment
- Disposable - Carry Stuff
- Disposable - Military
- Disposable - Medical
- Credit Card
- Creature Comforts
- Weight Reduction In Cars (Seats)
- Personal Safety - Climbing?
- Medical - Hold Things Open, Then "Melt"
- Disposable Watches
- Disposable Anything That Gets Dirty/Food On It
- Disposable Airplane Stuff?
- Constant Force LEM
- Third World Agricultural Applications
- Third World Hygiene Products
- Popup By Curling The Sheet
- Military Structures
- Outer Space Structures
- Roll-Up Arrays