Investigation of Deployable Structures and Their Actuation

by

Logan Munro

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ABSTRACT

Deployable Structures had not been designed for use in the oil field industry, and additionally have not been designed as devices to perform mechanical work. By analyzing deployable structures a detailed understanding of the mechanism kinematics has been developed. Further, we have analyzed new design concepts of deployable structures that include void filling alterations and snap fit strengthening. The actuation and mechanical loading of the structures and the input to output force ratio were investigated. This understanding was applied to several actuation methods.

Thesis Supervisor: Anette E. Hosoi
Title: Associate Professor of Mechanical Engineering

1. ACKNOWLEDGEMENTS

I would like to thank Dr. Julio Guerrero for his incredible efforts in advising me during the production of this thesis and beyond, and for exposing me to oil field research. I would also like to thank Schlumberger for supporting this thesis.

CONTENTS

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2. INTRODUCTION

2.1 Deployable structure definition

A Deployable Structure (DS) is any mechanism that can expand from enclosing a small area or volume to enclosing a larger area or volume. DS combine rigid linkages and joints in a configurable closed-loop mechanism; see Figure 1 for examples.

2.2 Background and Objectives

Downhole operations in oil field exploration require tools to convey material to the well wall, and tools that perform mechanical work. Most mechanical systems in the downhole environment convey parts radially by employing mechanisms such as sliders and pin joints distributed around the diameter of a tool. Deployable structures have the ability to solve some of the inherent faults seen in these traditional linkages and provide functional advantages of these mechanisms. A DS can transform a collapsed disc structure into an expanded ring several times larger than the initial diameter. Deployable structures can convey material into a cylindrical shape. DS have not as of yet been used to perform mechanical work either in the downhole environment or elsewhere. This work investigates the use of deployable structures performing mechanical work and the force advantages that can be generated. Methods of expanding DS have been proposed that will allow the use of DS downhole for these and other applications.

An alternative structure capable of conveying material radially is the compliant mechanism. With respect to compliant structures, a DS can achieve a greater range of expansion with a more robust design, suitable for the harsh environment found down-well. (Guerrero et al. [01])

By exploring the existing knowledge and embodiments of expandable mechanisms and how they relate to deployable structures, this report investigates the generic implementation of a deployable structure. Through an understanding of the deployable structure kinematics, we are able to describe actuation methods that exist and can be useful for downhole applications. These actuation methods have been patented by Schlumberger (Guerrero and Munro [02]).

The report analyzes the previous work of deployable structures and develops parametric equations to describe the motion and force generation capabilities of DS. From this, an understanding of the forces developed and transmitted is tackled, followed by computer simulations and design of deployable structures. Finally, existing actuation methods are investigated and explained.

3. ANALYSIS OF PRIOR ART

The current uses of deployable structures are primarily limited to conveying material outwards, or for entertainment or for aesthetic functions. Deployable structures are seen in a limited variety of products such as camera apertures, children's toys, storage containers, sculptures and retractable roofing. None of these implementations contain an integrated actuation mechanism, nor are they used to transfer forces or perform work. This section investigates existing research in deployable structures based primarily in academia and relevant research and patents in the oil-field industry.

3.1 Deployable structures in academia

The inventions of Professor Sergio Pellegrino [03] have been studied for their ingenuity with regard to deployable structures. Hoberman [04], [05], [06], [07] and [08] holds several patents in the area of collapsible structures in addition to Zeigler [09]. These inventions are all variations of foldable structures that cover some spherical surface.

Pelligrino's "*Expandable/collapsible Structures*", [03] is the closest prior art to the mechanism investigated in this report. However – for use as a downhole structure – the device proposed in Pelligrino's patent has the following shortcomings:

a) the device is not capable of adjusting its deployed-state perimeter to the inner perimeter of the cylindrical space where it is deployed,

b) the device cannot be locked in a deployment state,

c) the device does not provide a means by which to actuate and deploy the structure,

d) the device has not been developed to transmit forces or perform work.

Figure 2 shows two different inner perimeters achieved by Pellegrino's invention, illustrating that a variety of closed loop shapes are possible and differences in configuration that can be produced from a simple repeated structure.

3.2 Oilfield related

An extensive search of previous patents related to deployable structures revealed there is limited prior art in the field. Shell has produced the most inventions of oilfield related expanding elements in down-hole environments. Out of 1000 patents, none describe deployable structures; instead Shell's patents all describe tubular systems that are deformed plastically or elastically, but they are not mechanisms, see Figure 3, Figure 4, Figure 5, Figure 6 and appendix A.

3.3 Compliant mechanisms

There have been other attempts to develop expandable systems that adjust and conform their perimeter to the inner perimeter of a cylindrical space where deployed. Some of these have used compliant mechanisms that expand and collapse in order to cover different geometries and areas. Some of these attempts are: "*Compliant mesh structure for collapsible reflector*" (US patent 3982248A), "*Foldable assembly of like size and shape structural members, foldable for handling, packaging, shipping, and storage, and unfolded and utilized as principal members of structures*" (US patent 5448867A). "*Mechanical end face seal ring having a compliant seal face*" (US patent 6299173B1), which uses compliant elements arranged around a sealing ring, each of them deforming like cantilever beams. "*Self aligning connector bodies*" (US patent 6379071B1) uses compliant rings and dowel pins to facilitate the alignment of parts during assembly. None of these embodiments provide details for actuation and none are designed primarily to transfer forces or work.

3.4 Biomedical

Some interesting applications of related mechanisms have been found in biomedical devices. In addition one of the devices most closely related to the examined device is "*Method and apparatus for radical prostactetomy anastomosis*" (Patent

WO2004000137A2 (A2,A3)), which has an inflatable anchoring module that allows it to anchor with respect to the cylindrical surface of the organ operated upon. This system also has devices that are expandable in the axial direction. The patent *"Implantable self-expanding prosthetic device"* (US patent 20050090893A1) is a system composed of compliant cells made of U-shape wires that conform to a circular tubular contour; it is less stiff in the axial direction than in the radial direction which allows it to be retracted by pulling in the axial direction.

3.5 Conclusions about previous art

It can be summarized that deployable structure related patents are focused in the following areas: apertures, collapsible structures, bio-medical devices, and other various and isolated applications. From all of the prior art analyzed, nothing has described the use of deployable structures specifically for downhole use or as a method of transferring forces, as is analyzed in this report. The prior art is missing both the application of DS as a down-hole tool as well as the actuation mechanisms required.

4. CONCEPT AND MODELING

This section discusses the theory behind the deployable structure presented in this report, represented in Figure 7. The general equations are presented and the results of computer aided modeling are shown.

For the generic circular structure, the important variables to consider are the initial diameter and the final diameter (Figure 8). These can be non-dimensionalized to an expansion ratio where:

$$\text{Expansion Ratio} = \frac{\text{Outer Diameter}_{\text{initial}}}{\text{Outer Diameter}_{\text{final}}}.$$

The actuation of the circular structure creates a leverage of forces through the mechanism, (Figure 9) from the inner perimeter forces to the outer perimeter forces. This ratio of the output force of the structure to the input force is the force ratio:

$$\text{Force Ratio} = \frac{\sum \text{Force}_{\text{inner}}}{\sum \text{Force}_{\text{outer}}}.$$

4.1 Deployable structure concept

The primary element of the closed-loop deployable structure expansion is the "scissor linkage". A scissor linkage allows for a mass transfer from one axis to another, for example from the X axis to the Y axis in a simple lazy-tongs example, Figure 10 and Figure 11. A closed loop structure is essentially a set of lazy-tongs that have been bent into a circle, and connected at each end. Discussion of the DS will be in cylindrical co-ordinates, as shown in Figure 12. Variations in the shape and connection of the scissor links can manipulate the mass transfer in different ways, and can create a closed loop deployable structure. For a desired circumferential expansion, mass is either transferred from the Z-axis (shortening the mechanism, Figure 13a), or from the R-axis (thinning the mechanism, Figure 13b), or a combination of both. Considerations in device use and kinematic stability indicate a constant axial length is favorable, i.e. the mechanism should "thin," and contract radially, rather than shortening. In this manner, segments can be stacked on one another to create a device of constant length.

4.2 Modeling

The equations describing a deployable structure were derived for an idealized device and can calculate expansion ratios, part lengths and joint positions. These equations are described in this section.

To facilitate the design of the DS, the entire structures were modeled in Pro/ENGINEER CAD software. This allowed dynamic altering of link number, part length and geometry, and provided an invaluable resource in determining interferences, visualizations and design insights.

4.2.1 Equations

This section describes the governing equations for a simple circular expandable structure. An expandable ring is composed of several "angulated elements," Figure 14. Each angulated element consists of links between joints. A standard scissor type lazy-tong device connects these joints co-linearly. To produce a circular or closed loop structure, each link offsets a joint at an angle. The number of links directly determines the final shape. For example, 8 links will expand to a regular octagon and *m* links will expand to a regular polygon with *m* sides. The number of links in each element determines the angle, θ, between each link:

$$\theta = \frac{2\pi}{m}.$$

Two angulated elements compose a scissor element, Figure 15, which we will call a *petal.* Each petal occupies a sector of the ring of size θ. For a large number of petals, size approximations can be made for quick analysis. The approximate closed diameter (Figure 16) depends solely on the number of links per petal, *n*, as well as then length of each link, *L*:

$$D_i \approx 2nL.$$

However, in the expanded state, Figure 17, it is the number of elements (*m*) that primarily affects the diameter:

$$D_f \approx \frac{2mL}{\pi}.$$

Thus, to a first approximation, the expansion ratio of a closed loop DS is

$$\text{Expansion Ratio} \approx \frac{m}{n\pi} = \frac{D_i}{D_f}.$$

Therefore, to maximize the expansion ratio of the DS, each link must be in its simplest form where $n = 2$, Figure 18, giving each angulated element three distinct points, or joints. The number of petals, *m*, should also be maximized, but this is subject to other constraints.

The three angulated element joints are designated as follows: *internal vertex, joined vertex* and *external vertex*, Figure 19, named for their collapsed position with respect to the circle. The controlled vertex for discussion will be the inner vertex. As the inner vertex is translated outward, the joined and external vertices also move outward. Related to the radius (from the center starting point) of the inner vertex, r, and the angle at which each petal is offset, θ, where $\theta=2\pi/m$, the radial distances of each vertex is shown below.

Outer vertex radius (R_O):

$$\mathrm{R_O} = 2\cos\left(\frac{\theta}{2}\right)\left\{\sqrt{L^2 - r^2\sin^2\left(\frac{\theta}{2}\right)} + r\cos\left(\frac{\theta}{2}\right)\right\} - r .$$

Joined vertex radius (R_J):

$$\mathrm{R_J} = \left\{\sqrt{L^2 - r^2\sin^2\left(\frac{\theta}{2}\right)} + r\cos\left(\frac{\theta}{2}\right)\right\} .$$

L is then length of an individual link, and R_J and R_O are the radii of the joined and outer vertices respectively from the center of the expansion. These two equations fully describe the motion of a DS in space.

4.2.2 Computer modeling

This section describes the computer aided modeling of the DS. Modeling was performed in Pro/ENGINEER, a 3-D parametric modeling code. In this environment the entire mechanisms was constructed. The Pro/ENGINEER model parameters could be freely altered: for example, the number of petals, or the shape and size of the device. This stage of development allowed for adaptation of beam and joint thickness, as well as construction of the files used for manufacturing of the device. This was the final step before the manufacture of the device.

4.3 Kinematics

This section describes the movement and expansion of the DS. The use of parametric modeling for the linkages provided a significant amount of information both conceptually and analytically, and the 3-D parametric model confirmed the numerical predictions. With the device model entirely configurable, manipulation required little effort, and new shapes and ideas could be visualized rapidly. Further analysis provided a small discovery regarding the stability near maximum expansion.

4.3.1 Localized stability

A reference for describing the expansion of the structure is required. The two references will be an inner inscribed circle radius, and an outer circumscribed circle radius as illustrated in Figure 20. In a simple DS, there are three distinct expansion states. The first occurs when the outer shape of the device reaches that of a regular polygon of number *m*. Further expansion places the outer shape into a regular polygon, now of number *2m*. The next state occurs when joint members overlap perfectly and form a regular polygon again with number *m*. This final state is only theoretical as it assumes zero joint thickness.

What is important is that, even though the inner diameter is expanded, the outer mechanism is not always expanding. A polygon of number *m* has a larger average diameter than a polygon of side *2m*. Therefore, a small dip in outer diameter is seen near full expansion, Figure 21.

It is hypothesized that this dip will provide a source of stability. If the device is expanded past the first state, and allowed to reach state 2, an external force, if applied correctly, should not necessarily collapse the structure. This is because to collapse, the external diameter would need to increase marginally before fully collapsing. Therefore a range of stability is achieved. This prompted the design of the DS to be in state 2 at the desired expansion.

4.3.2 Force Multiplication

The mechanism of a deployable structure can be used to exert forces radially either externally (on the outer joints) or internally. The mechanism creates a mechanical leverage between the internal forces and the external forces. We will define this leverage as a force ratio between the input forces and the output forces for a gripping device (internally):

$$\text{Force Ratio} = \frac{\sum \left|\text{Force}_{\text{inner}}\right|}{\sum \left|\text{Force}_{\text{outer}}\right|}.$$

Using the concept of virtual work, the input forces are related to the output forces in by the following:

$$\sum \left|Force_{Outer}\right| \cdot \Delta R_O = \sum \left|Force_{inner}\right| \cdot \Delta R_i .$$

Before this is solved analytically, consider the expansion of a generic DS, typified in Figure 8. A DS initially is a solid disc, and upon expansion becomes a thin ring. The inner most vertices, specified by R_i expand from basically 0 to almost R_{final}. The outermost vertices, R_O expand from $R_{initial}$ to R_{final}. Therefore, the innermost vertices expand a greater distance than the outermost vertices. On full expansion:

$$\Delta R_i > \Delta R_O .$$

Given the virtual work constraint of work in equals work out, this means that – for a given force on the outer vertices – the required forces on the inner joints must necessarily be less than those on the outer joints.

$$\begin{aligned}
&\Delta R_i < \Delta R_O \\
&Force_{Outer} \cdot \Delta R_O = Force_{inner} \cdot \Delta R_i \\
&\therefore Force_{outer} > Force_{inner}
\end{aligned}$$

Therefore, theoretically there is a mechanical advantage from the inner joints to the outer. Using virtual work, this ratio can be calculated from the equations of diameter presented earlier. This mechanical advantage has been determined analytically with the aid of the

Matlab computing environment. Using virtual work, it was shown that the force multiplication ratio is always less than 1 when transferring force to the center (i.e. a griping action) and that the force transmission ratio increases with the size of the device (*L*), as shown in Figure 22. This graph illustrates the declining force transmission ratio from external nodes to internal nodes of a DS at high expansion for a DS with 12 links (m=12). *L* length corresponds to the length of an angulated element and is therefore correlated to the size of the device. As the structure approaches its maximum expansion, the force transmission between the inside and the outside drops considerably. Additionally, it should be noted that the transmission ratio approaches 100% asymptotically as *L* approaches infinity. The inner diameter ranges from 32 mm to 86 mm corresponding to standard tool diameters of 1.25 in. to 3 3/8 in.

5. EMBODIMENT DETAILS

5.1 Shape

This section will describe the shape of some prototype embodiments that have been patented by Schlumberger. In summary, a design was modified to produce a rigid, gap-less device, Figure 23. The first design iterations considered only straight links as shown in Figure 24. The next step was to alter the shape to create a truly circular perimeter as opposed to a polygon. This was achieved by adding curved sections to each link (Figure 25). Next, thickening the part at strategic locations eliminated wall gaps when the layers were stacked (Figure 26) to provide a continuous 3-D structure.

5.2 Snap fit

To prevent collapsing and provide strength to the deployed device, a snap fit mechanism was designed. The snap fit integration provides a useful tool for down-hole applications where strength and reliability are paramount. As mentioned above, the design of the DS was inside a stability range that could significantly increase the resistance to collapse. The shape of the structure of the DS prompted an analogy to an arched bridge. To accentuate the arched bridge concept additions were added to provide a continuous band of material when fully deployed causing the device to “lock together” when stressed (Figure

27). These additions provided the material for a mechanical locking snap fit mechanism to further strengthen the device.

Snap fits fall into three basic categories: in-plane motion, out-of-plane motion and annular (Figure 28). In each of these categories there are two distinct subsets: resistive and permanent snaps, as shown in Figure 29. A resistive snap is designed to provide a weak hold, such as those found on cabinet doors, while a permanent snap fit is designed to remain in place, such as a remote control plastic assembly cover. The prototype was designed with an in plane snap to allow for effective stacking of layers. The first prototype had only one snap position at full expansion (Figure 30). The next iterations had a ratchet mechanism to hold the device stiff in several different expansion states (Figure 31). This would provide a greater flexibility in use as the device would remain rigid at different expansion states.

5.3 Manufacture

Figure 23 shows a layered prototype of the DS. The individual link is shown in Figure 32. The petal is composed of two links and is the primary component of the device. The mechanism is entirely constructed from these two-dimensional components. Each layer consists of 9 petals stacked back to back, but this number can be anything larger than three. Additional features such as a snap fit or void filling (to achieve a smooth outer surface) are provided by a separate feature rigidly attached to the petal (Figure 31).

The devices shown were cut from ¼" aluminum 6061 sheets on a two-axis abrasive water-jet system (OMAX). Minimal machining of the part was required after water-jet cutting. Each petal has five holes, two of which connect the additional void-fill pieces, and the other three are pivots. These joints were connected with 1/16" threaded rods to facilitate joining them.

At large expansion ratios, the joint thickness plays and important role, specifically the inner most pivots. As such, in the prototype shown (Figure 33) the joints were modified to allow the parts to fit together closely.

6. ACTUATION AND DEPLOYMENT

This section will describe some of the proposed methods of actuating a DS. Deploying a DS consists of changing the size and shape from a collapsed and reduced shape to an expanded shape. Actuation is required to control the expansion and fully utilize the benefits of a deployable device. However, actuation of the device is not trivial, specifically because the only stationary reference point is in the center of the device, which is often desired to be void.

6.1 Description of actuation systems:

Successful actuation of the generic deployable structure occurs when at least three pivot points are translated radially from a center. This section describes different methods of mechanical actuation and their advantages and disadvantages.

6.1.1 Rotating actuation

This mechanism uses the rotation of a wedge shape to expand and retract the deployable structure. A disc with radial slots, $Disc_{fixed}$, will provide a path for the joints to follow (Figure 34). Three joints will be constrained inside these slotted grooves and the grooves of a second disc, $Disc_{rotating}$. This disc is used to provide a wedge, (Figure 35). The two discs are located co-radially and the joints of the deployable structure are constrained to move where the slots of the two discs overlap. On rotation, the spiral shape of $Disc_{rotating}$ will push the joints along the radial slots of $Disc_{fixed}$, deploying the structure (Figure 36).

(Polar co-ordinates will be used to describe the discs and their rotation.) The rotation angle of the Discrotating is $\theta_{rotating}$; angular velocity is $\dot{\theta}_{\mathrm{rotating}}$ and the torque exerted on $Disc_{rotating}$ is $T_{rotating}$. The location of the device joints is R_{device} and the force exerted on each joint due to the torque, is F_{device} (Figure 37).

Energy conservation dictates that the speed of expansion of the deployable device ($\dot{\mathrm{R}}_{\mathrm{rotating}}$) is inversely proportional to the force of expansion, F_{device}, that is:

$$\dot{\theta}_{\text{rotating}} \cdot \mathrm{T}_{rotating} = \dot{R}_{device} \cdot \sum \left| F_{device} \right|$$
$$\rightarrow \dot{R} = \dot{\theta} \frac{\mathrm{T}_{rotating}}{\sum \left| F_{device} \right|}$$

The quantity

$$\frac{\mathrm{T}_{rotating}}{\sum \left| F_{device} \right|}$$

is the ratio of the torque exerted on the system to the force exerted on the device. This ratio is essentially the force multiplication ratio. The force multiplication ratio can be altered by changing the shape of slotted paths on *Disc_{rotating}*. For example, a *Disc_{rotating}* with slotted paths that have a length several times that of the disc's radius will produce a large expansion force, but will subsequently require multiple rotations of the disc to fully expand the device (Figure 38). The slotted paths are a function defined in polar coordinates: r = f(θ). Note that the derivative of the path radius with respect to θ gives the torque multiplication factor:

$$\frac{dr}{d\theta} = \frac{\mathrm{T}_{rotating}}{\sum \left| F_{device} \right|}.$$

In general, the function of a device determines the desired force multiplication, which can be suited for different applications. For example, a disc that produces a constant force multiplication regardless of expansion diameter has the slotted path equation of:

$$r = a \cdot \theta$$

where *a* is the force multiplication. A constant force multiplication ratio could be used in applications where a single desired force is at several different radii. Different jobs require different force multiplication ratios which can be generated by altering the slotted path shape. Essentially a path for each specific desired force ratio could be created.

6.1.2 Geared mechanism.

The expandable structure incorporates mechanical joints to connect the rigid links. These joints can be directly connected with gears to drive the expansion and contraction, as shown in Figure 39.

There are two implementations of this system, depending of whether the device is used for external or internal loading. In both instances, a smaller gear is located at the center of the angulated element. For external loading the larger gear is centered on an inner pivot, for internal loading, on an outer pivot (compare Figure 39a and Figure 39b). The larger gear is rigidly connected to the angulated element, while the smaller gear is freely rotating.

Figure 39a illustrates the use of a large gear on the innermost pivot. This provides minimal interference between the gear and space external to the device and is therefore suited for use in a device applying an external load. Figure 39b illustrates the concept designed with an internal clearance of the device, allowing a load to be applied internally without interference from the gear. Note the shape of the larger gear in Figure 40: an unused portion of the larger gear is removed to allow full expansion without either internal or external interferences, and the entire two gear system is incorporated within the thickness of the deployed device.

The geared device can be actuated by rotating either the fixed or the independent gear. The ratio between the two gears determines the torque multiplication of actuation, which can be varied as desired. As drawn there is a torque advantage if the smaller gear is used to drive the system. Further constraints would be needed to fully define the geared actuation method in space.

6.1.3 Extended arms

Providing an extension onto the arms of the structures can create a force advantage and a useful mechanism for actuation. The extensions can be on the outside (for an internally loaded mechanism) or internal (external loading) shown in Figure 41. This is perhaps the simplest method of generating a force multiplication. This solution would again need constraints to define its position in space.

6.1.4 Pistons

The individual petals, upon expansion, scissor and change shape. The innermost and outermost joints connect along radial lines. To actuate, a piston or (or other length changing device) would shorten this radial distance, or would, conversely, increase the tangential spacing of the joined vertexes. A simple example of this is shown in Figure 42. To provide large forces for both contraction and dilation it would be necessary to have opposing sets of pistons.

Similarly, any mechanism that can draw in or push out two points can be used to actuate the device. Figure 43 illustrates a device with a screwed thread attached between two joints. Rotation of the thread brings the joints together, whereas counter-rotation separates them, providing an actuation mechanism for the structure.

6.1.5 External linkage

All the joints on the expandable structure follow a radial path. However, there is no single part of the structure that, in a concentric expansion, remains motionless. Providing a linkage to allow the structure to expand can be provide through a mechanism that follows the required radial path, or simply a straight line passing through the center. The Peaucellier-Lipkin linkage provides a linear path, shown in Figure 44, through inversive geometry.

A combination of this linear motion linkage and the deployable structure can fully define the expansion and contraction of the mechanism. Additionally, the linkage can be place external to the device (Figure 45) for internal clearance, or internally (Figure 46) for giving external clearance.

This embodiment has several useful aspects. Primarily, this proposed mechanism has fixed anchor locations. Additionally, this mechanism can deploy the structure with pure, un-translating rotational motion. Furthermore, with three independent Peaucellier-Lipkin linkages, the device is fully constrained to expand concentric to a location. If two linkages were connected via gears, then this alone defines the expansion fully and could be a viable method of deploying the device. Thus, this linkage can be incorporated into all the previously explored concepts and provide a constraining base for expansion, if not used by itself for actuation.

6.2 Conclusion of actuation mechanisms

Several patented actuation methods exist for deployable structures, all with very different functional properties. The environment in which the structure is used and whether the device is to be used internally or externally will change the actuation method employed, as well as the desired force multiplication.

7. CONCLUSION

Most deployable structures have not been developed for downhole applications. More importantly, there is no existing structure developed that utilizes this specific structure to perform mechanical work. The analysis of expandable mechanisms has shown that certain deployable structures are valuable as devices to convey material and to exert forces. Certain deployable structures can be designed to perform mechanical work and can be optimized for mechanical advantage based on the required loading. We have specified the mechanical advantage of these structures as a known function of geometry and structure expansion (Section 4.3.2, Figure 22).

Furthermore, we have described and investigated issues that should be considered in the design and actuation of deployable structures. The mechanism can be adapted depending on whether the device is intended for internal or external loading. There is always a force reduction for deployable structures that receive the action load on the outer perimeter and exert a load with the inner perimeter. Conversely, an inner located force will be amplified through the DS externally. Yet in both these cases, the correct choice of actuation system can control the structure's overall force ratio. A developed understanding of the kinematics of the deployable structure has been presented in section 4.2.1. Furthermore, equations are available to predict the force multiplication over a range of device sizes and expansion ratios.

8. REFERENCES

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9. APPENDIX A

Appendix relating to shell:

The 4 patents from Shell that are most related to this area of inventions follow:

a) "*Method and system for reducing longitudinal fluid flow around a permeable well*", US7059410B2. Assignee: Shell, year 2006. Inventors: Bousche, Olaf Jean Paul; Runia, Douwe Johannes. This is an umbrella deployed in the well, it arranges a series of collapsed resilient sealing rings at regular longitudinal intervals around the permeable tubular before lowering the tubular into the well by means of tape and/or a binder which dissolves downhole. Figure 3 shows details of this invention.

b) "*Contractable* [sic] *and expandable tubular wellbore system*", GB2397084A, WO2003031771[A1]. Assignee: Shell, year 2004. Inventors: Lohbeck, Wilhelmus, and Christianus Maria. This is a ring with notches that allow it to be bent; it does not have an expansion ratio, because it does not expand, it just unfolds. Figure 4 shows details of this invention.

c) "*Foldable tube*", EP1073825b1. Assignee; Shell, year 2003. Inventors: Lohbeck Wilhelmus, and Christianus Maria. This is analogous to the previous one, but with more foldable facets. Figure 5 shows details of this invention.

d) "*Expandable wellbore assembly*", WO2005031115a1. Assignee: Shell, year 2006. Inventors: Lohbeck Wilhelmus, and Christianus Maria. This is a stent like expandable screen (Figure 6).

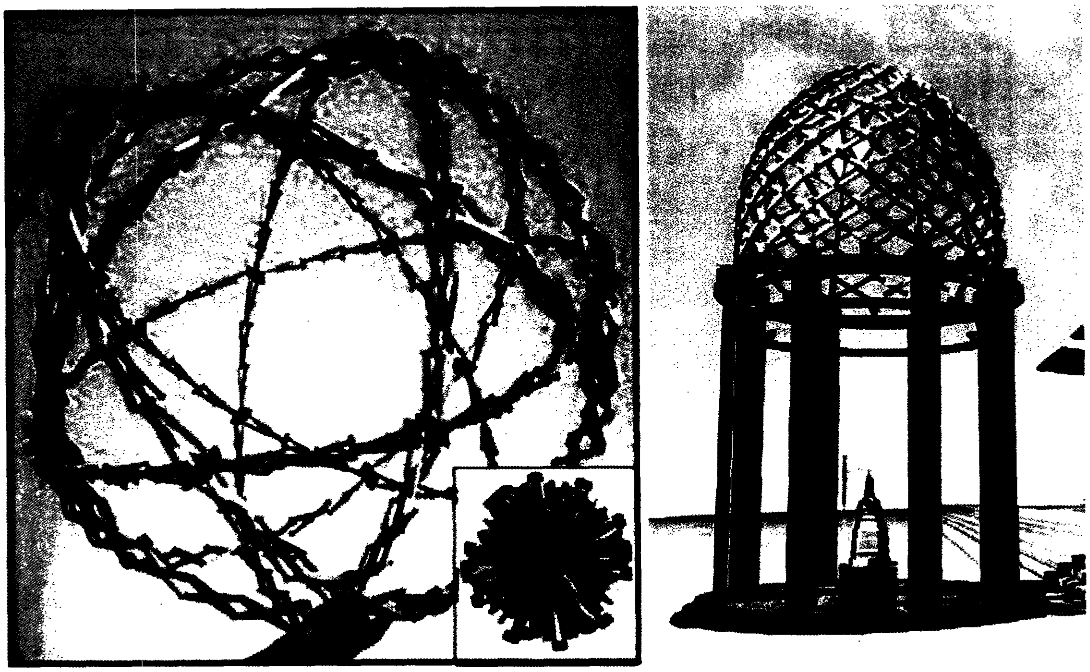


Figure 1 Implemented uses of deployable structures.
Left: the infamous "Hoberman Sphere" toy. Right: architectural design for an "EXPO 2000" work. (photos: hoberman.com)

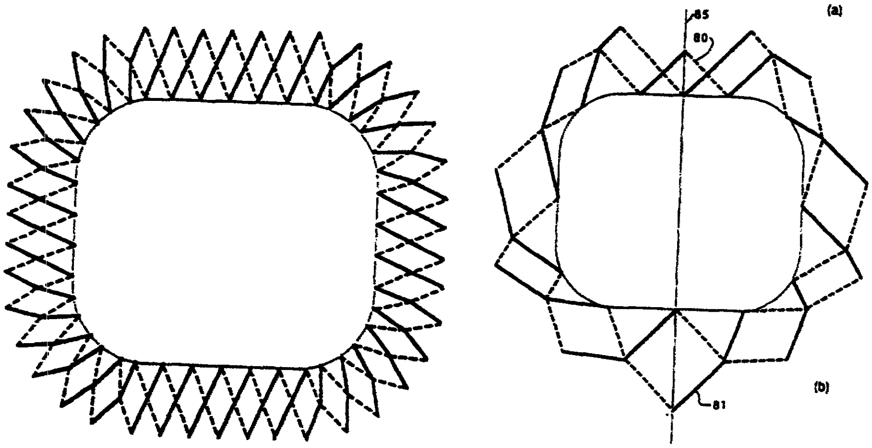
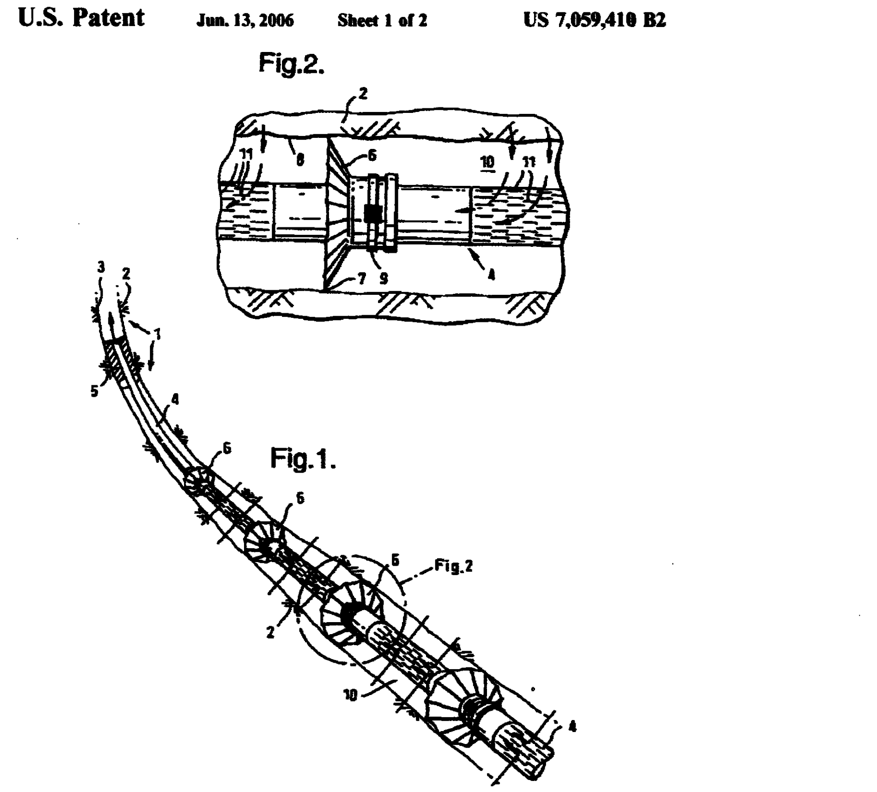


Figure 2 "*Expandable/collapsible Structures-A*" patent
Patent WO1997027369(A1), 1997, by Sergio Pellegrino.



U.S. Patent Jun. 13, 2006 Sheet 1 of 2 US 7,059,410 B2

Fig.2.

Fig.1.

Figure 3 “Method and system for reducing longitudinal fluid flow around a permeable well,” Shell patent
US patent 7059410B2. Assignee: Shell, year 2006. Inventors: Bousche, Olaf Jean Paul; Runia, Douwe Johannes.

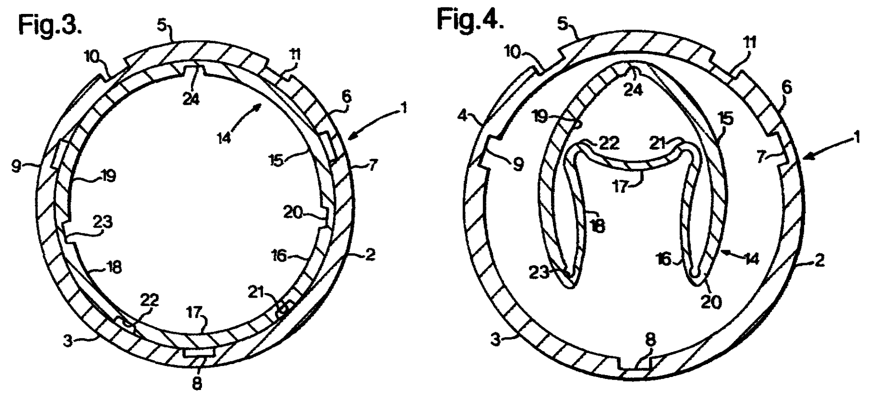


Fig.3. Fig.4.

Figure 4 “*Contractable* [sic] *and expandable tubular wellbore system,*” Shell patent
Patent GB2397084A, WO2003031771[A1]. Assignee: Shell, year 2004. Inventors: Lohbeck, Wilhelmus, and Christianus Maria.

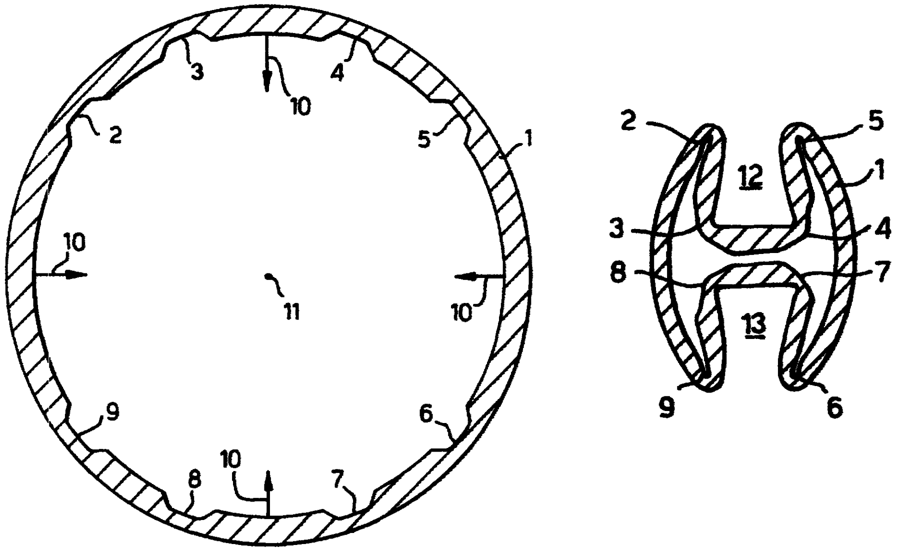


Figure 5 "*Foldable tube,*" Shell patent
Patent EP1073825b1. Assignee; Shell, year 2003. Inventors: Lohbeck Wilhelmus, and Christianus Maria.

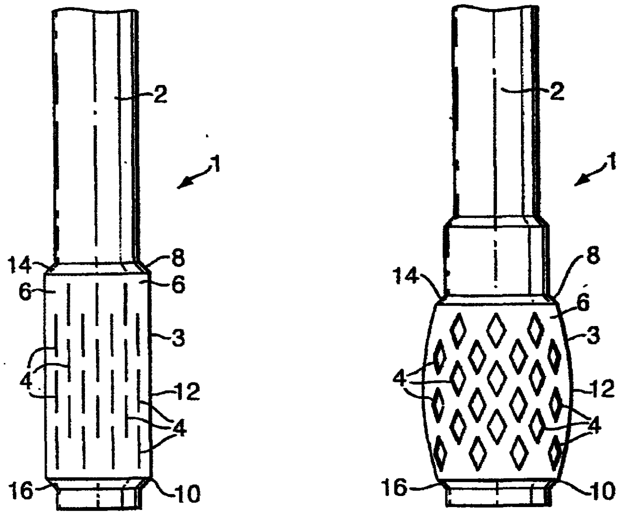


Figure 6 "*Expandable wellbore assembly,*" Shell patent.
Patent WO2005031115a1. Assignee: Shell, year 2006. Inventors: Lohbeck Wilhelmus, and Christianus Maria.

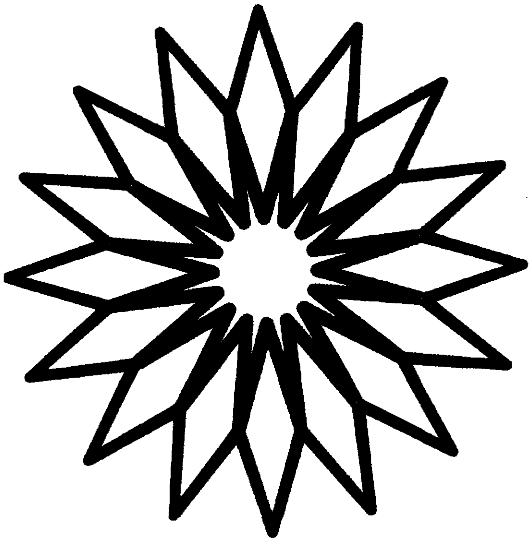


Figure 7 Generic structure of expandable structure

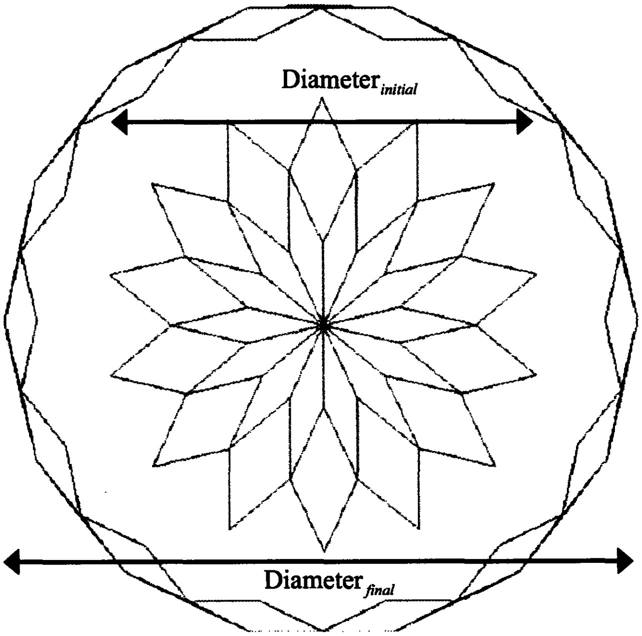


Figure 8 Expansion Ratio figure

This figure shows the difference in enclosed area of a contracted versus expanded deployable structure. Expansion Ratio = $\frac{\text{Outer Diameter}_{\text{initial}}}{\text{Outer Diameter}_{\text{final}}}$.

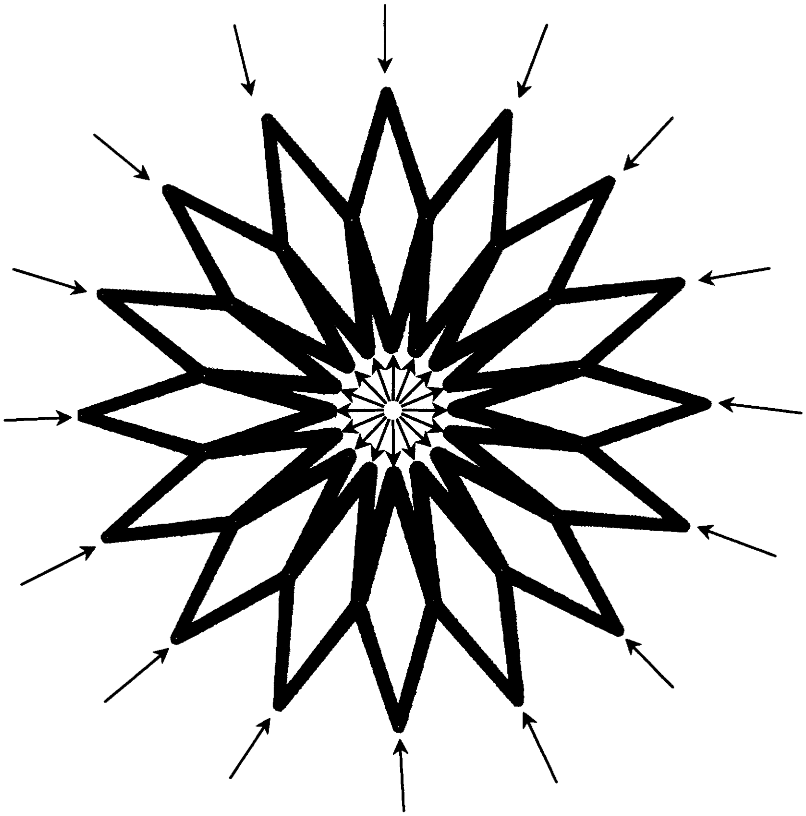
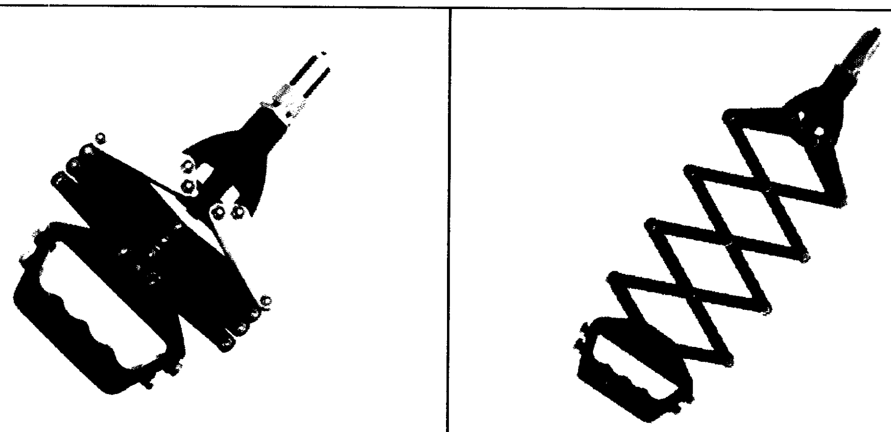


Figure 9 Deployable structure under actuation and opposing forces

$$\text{Force Multiplication Ratio} = \frac{\sum \text{Force}_{\text{outer}}}{\sum \text{Force}_{\text{inner}}}$$



(a) Closed scissor mechanism

(b) Expanded scissor mechanism

Figure 10 Scissor mechanism example; *lazy tongs*.

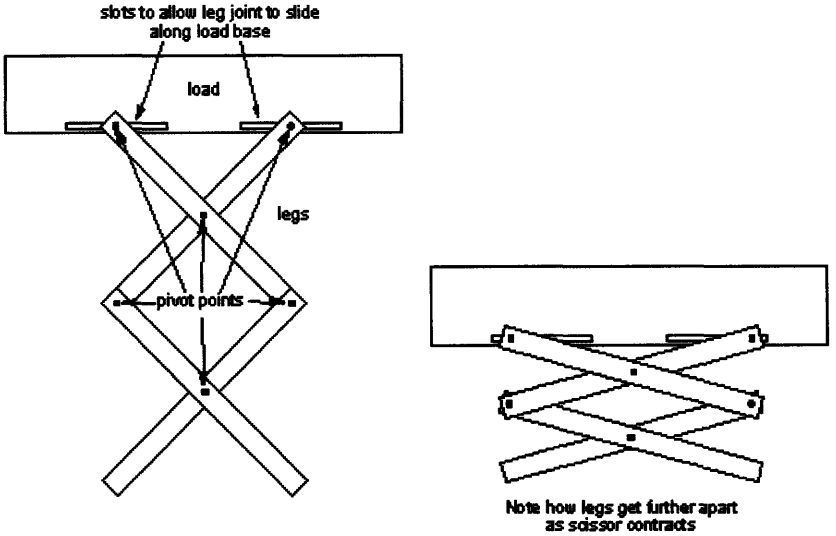


Figure 11 Schematic showing scissor linkage

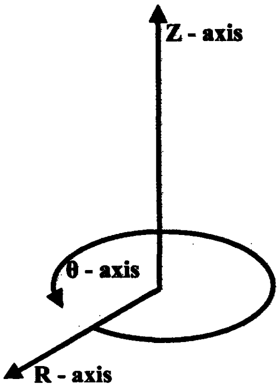
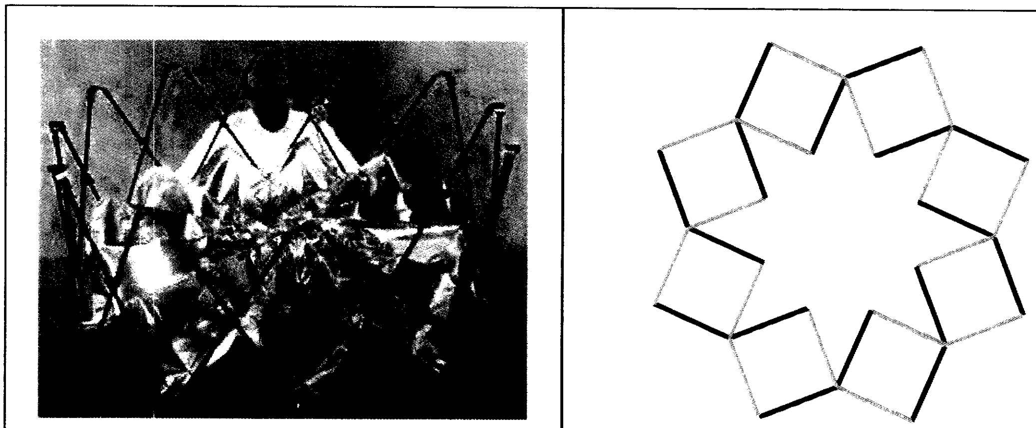


Figure 12 Cylindrical Co-ordinates



(a) Z-axis shortening

(b) R-axis shortening

Figure 13 Two modes of circumferential expansion in cylindrical co-ordinates

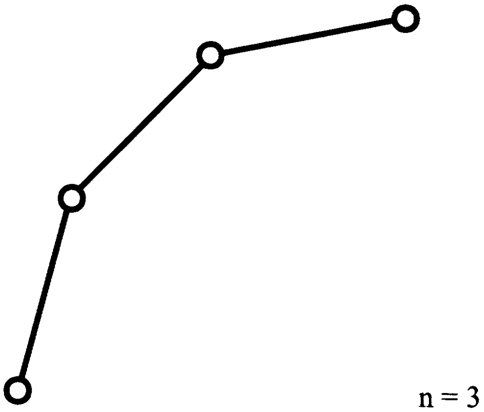


Figure 14 An angulated element

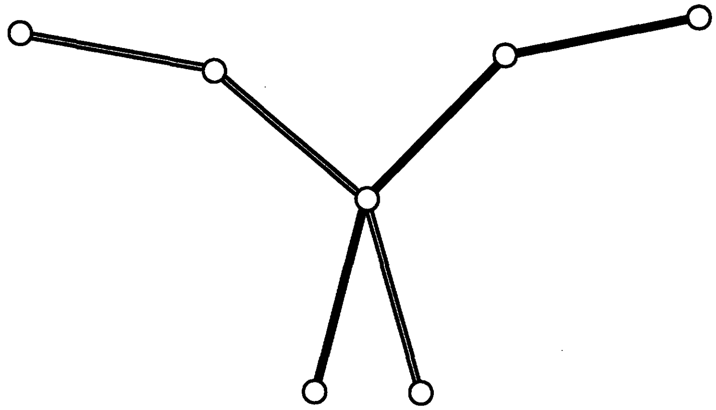


Figure 15 A single petal connected at one joint.

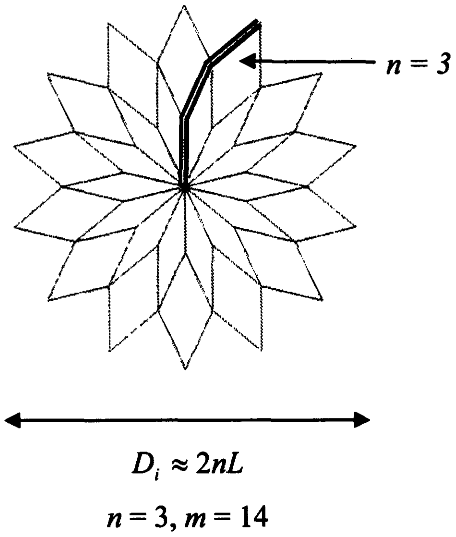


Figure 16 Simplified equation of diameter for a contracted deployable structure

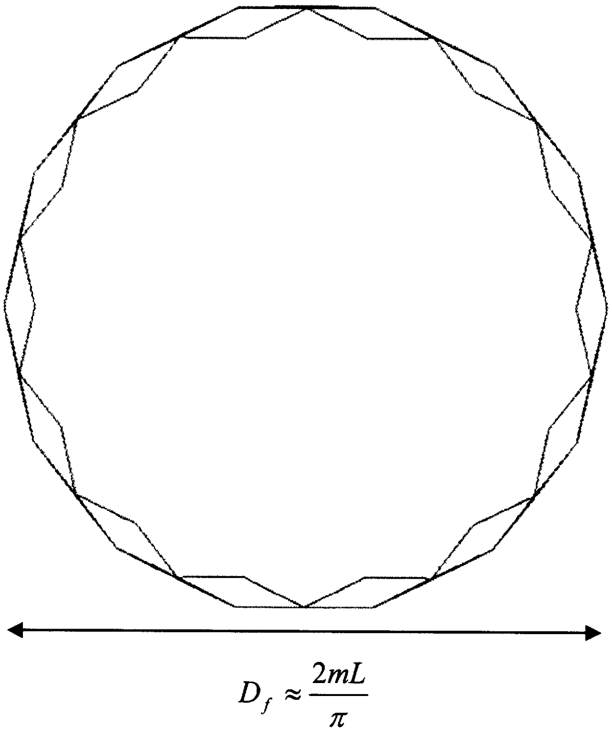


Figure 17 Simplified equation of diameter for an expanded deployable structure

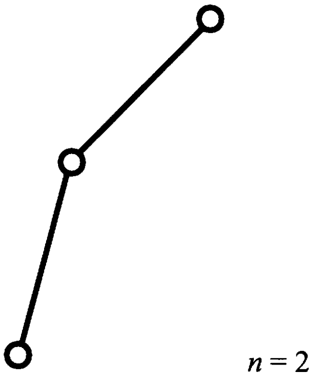


Figure 18 Simplest angulated element where *n* = 2

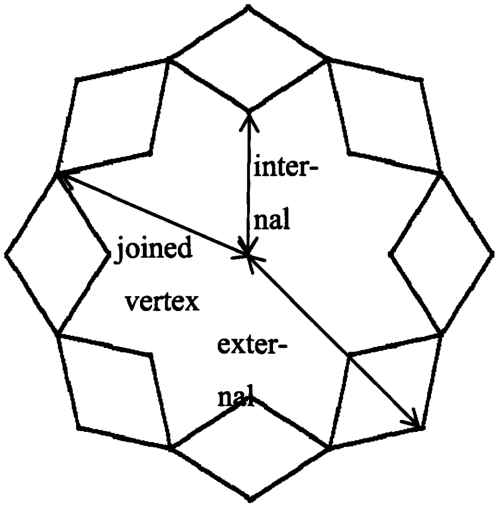


Figure 19 The three label joints of an angulated element.

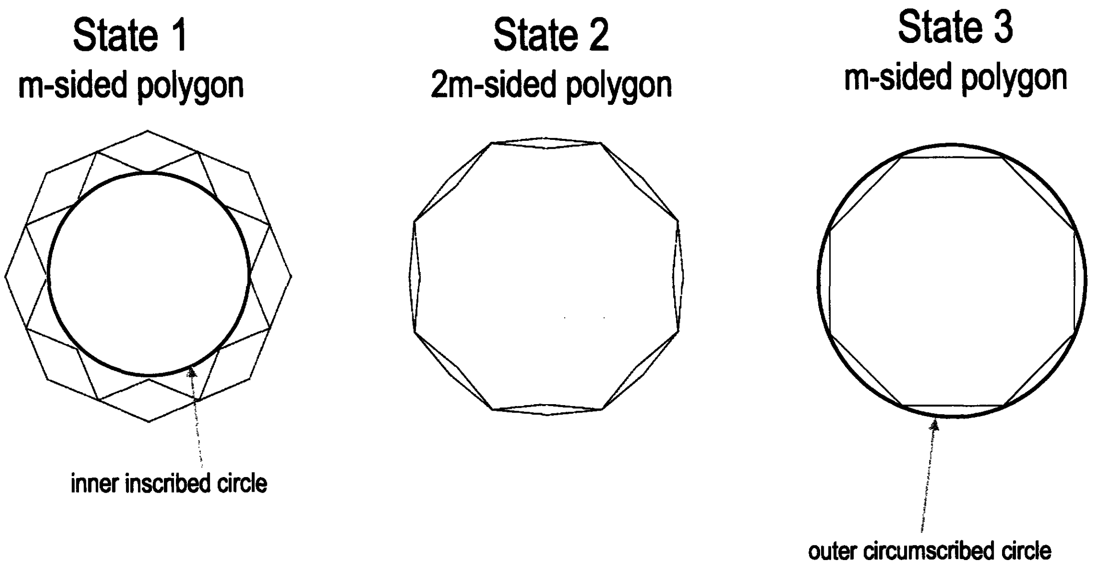


Figure 20 Expansion states 1, 2 and 3.

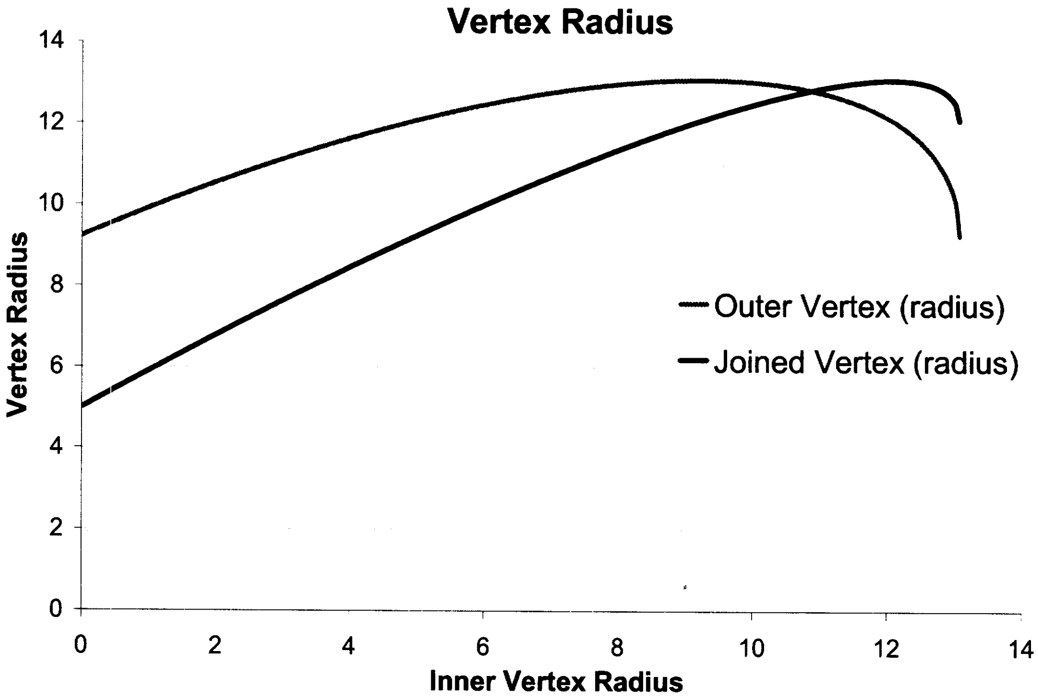


Figure 21 Expansion by vertex graph.

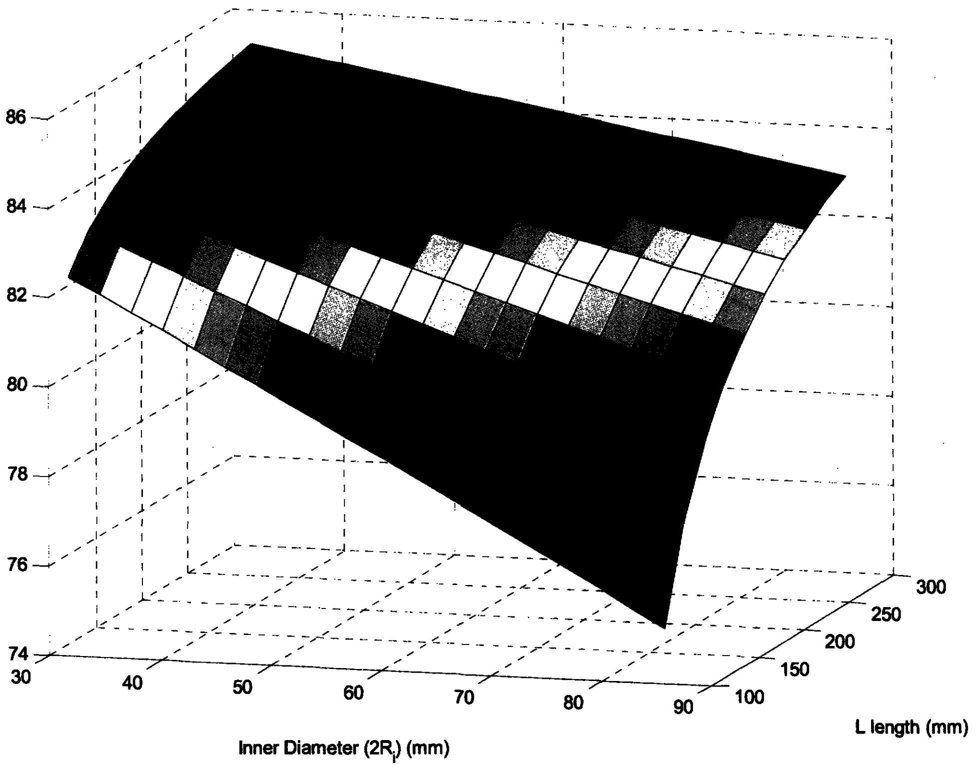


Figure 22 Graph of force transmission ratio as a function of inner diameter and device size.

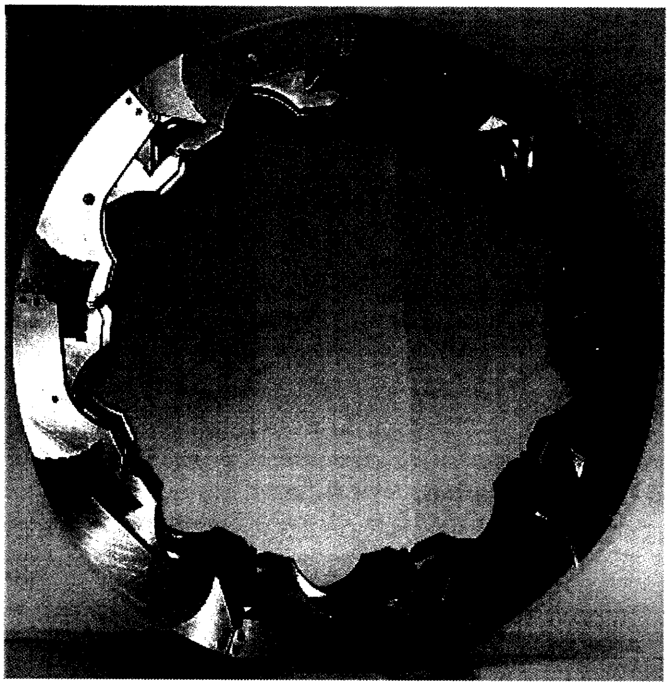


Figure 23 Layered, gapless Prototype

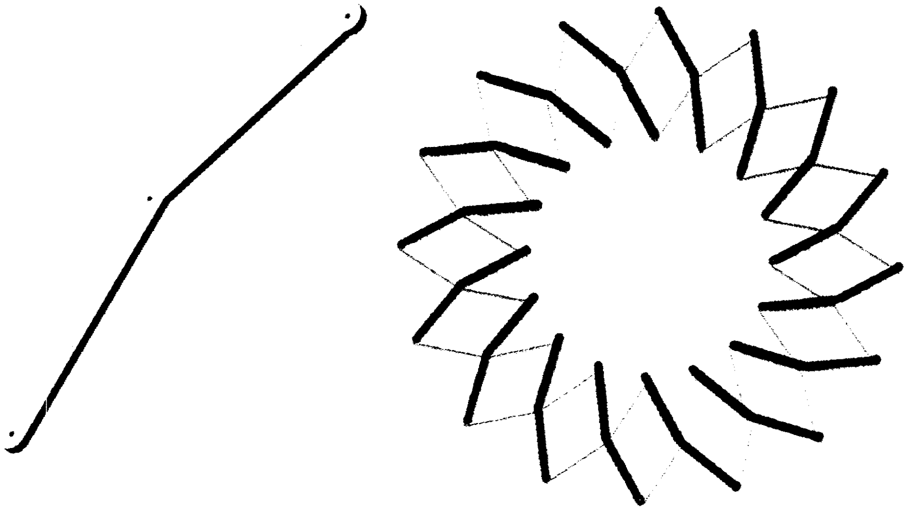


Figure 24 Straight link DS iteration

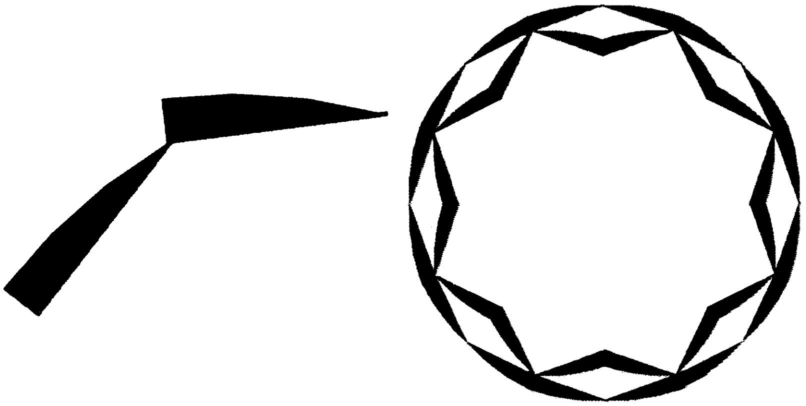


Figure 25 Curved link DS iteration.

Figure 26 Thickened link DS iteration

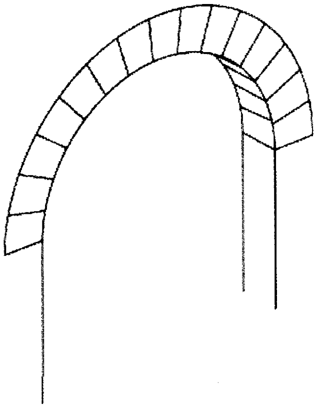
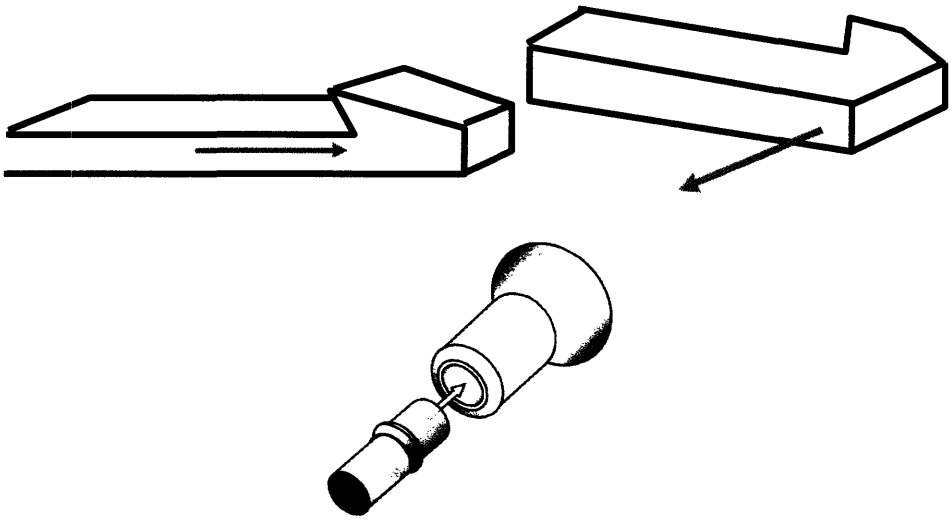


Figure 27 Arch



From: Bonenberger, Paul R. First Snap-Fit Handbook - Creating Attachments for Plastic Parts. (pp. 91). Hanser Publishers. Online version available at: http://tinyurl.com/2x5qon

Figure 28 Various snap fit types.

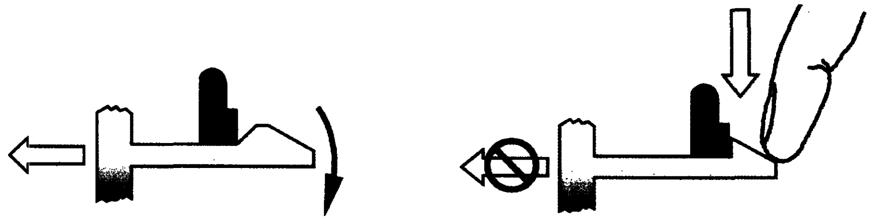


Figure 2.16 Non-permanent locks

Bonenberger, Paul R. First Snap-Fit Handbook - Creating Attachments for Plastic Parts. (pp. 29). Hanser Publishers. Online version available at: http://tinyurl.com/2x5qon

Figure 29 Releasing and non-releasing snap fits.

Figure 30 Single snap fit

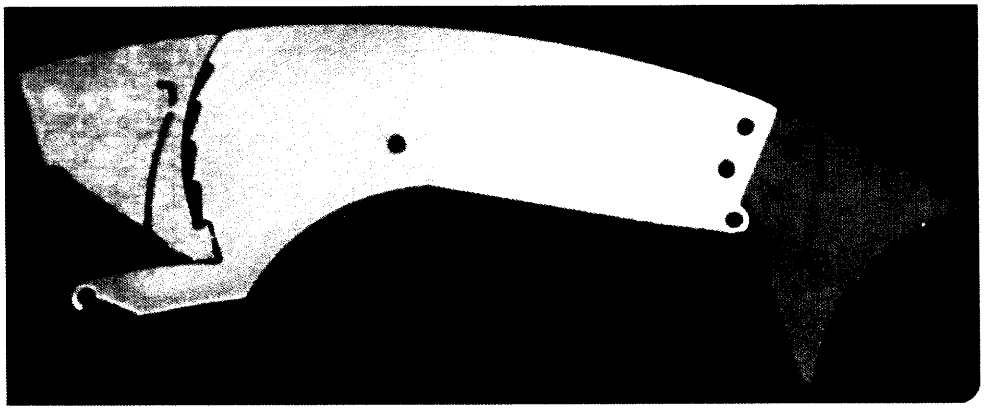


Figure 31 Ratchet snap

Figure 32 Individual element

Figure 33 Altered joint shapes of angulated elements.

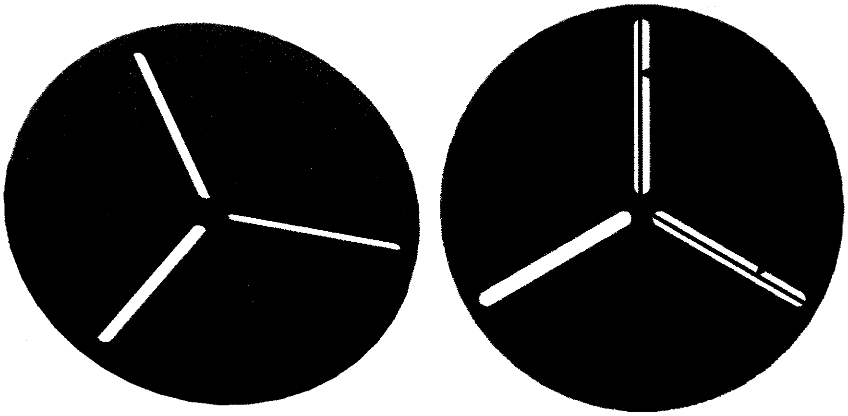


Figure 34 Schematic of ***$Disc_{fixed}$*****.**

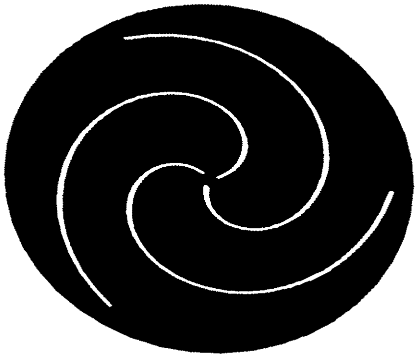


Figure 35 Schematic of ***$Disc_{rotation}$*****.**

The equation for the path here is: $r = 0.5 + 10\left(\frac{\theta}{360^\circ}\right)^3$

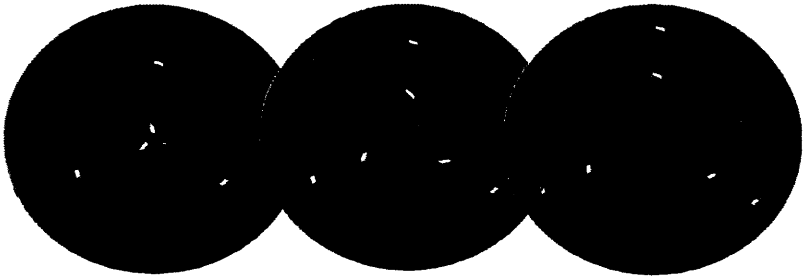


Figure 36 Time-lapse of rotating spiral disc on stationary disc.

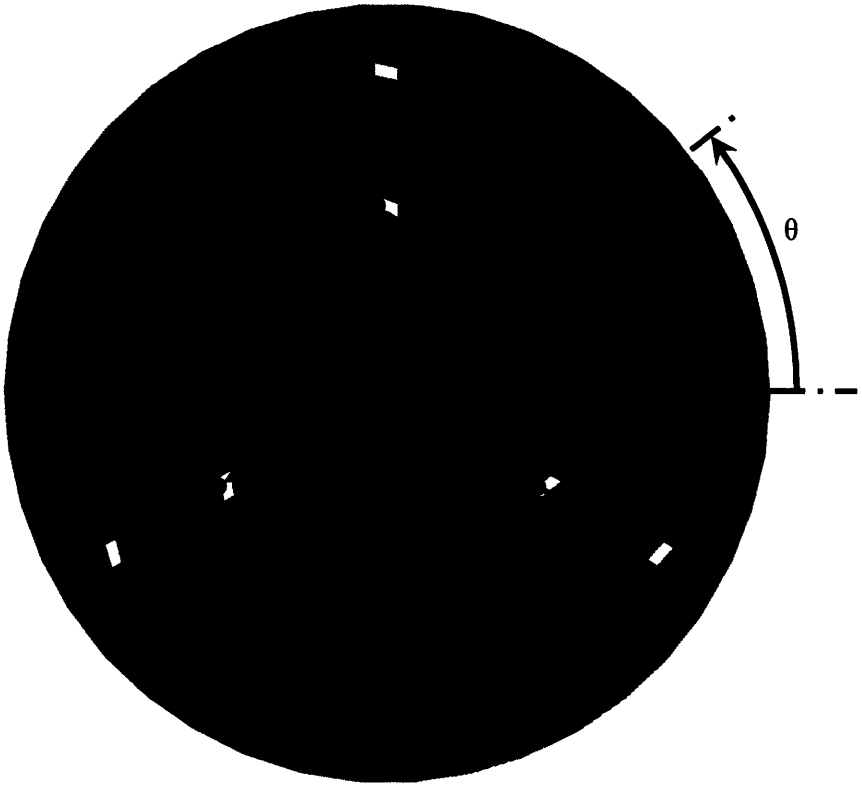


Figure 37 Annotated Rotational Device.

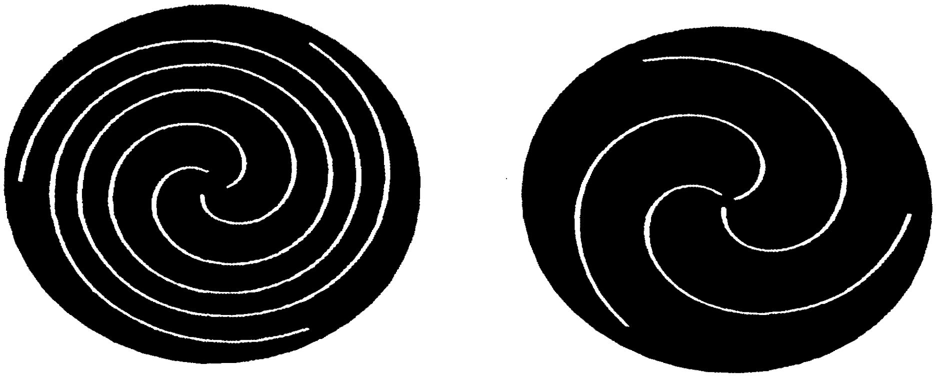


Figure 38 Comparison of increased path length spiral (left) to short path length

(right)

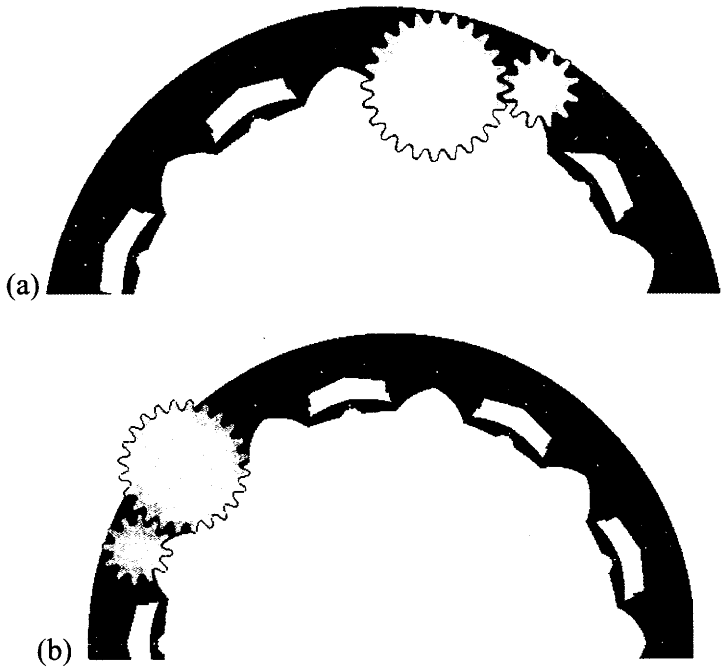


Figure 39 Internal and external use geared actuation mechanism.

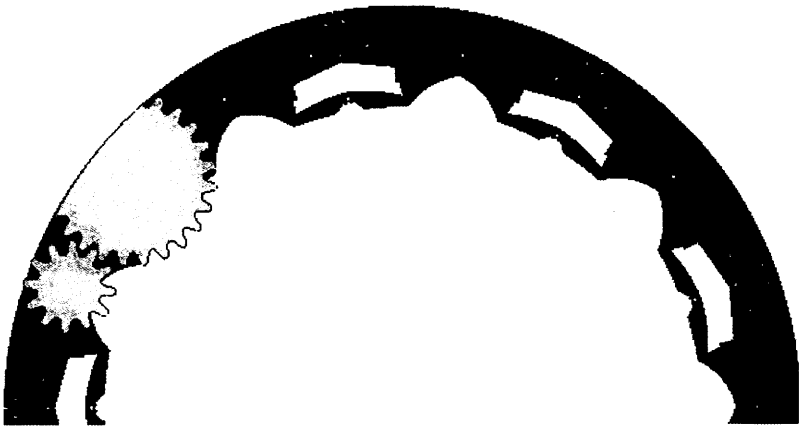


Figure 40 Multi-functional geared mechanism.
The gearing system is incorporated within the thickness of the device, allowing this device to be used as both an external clamp, or an internal grip.

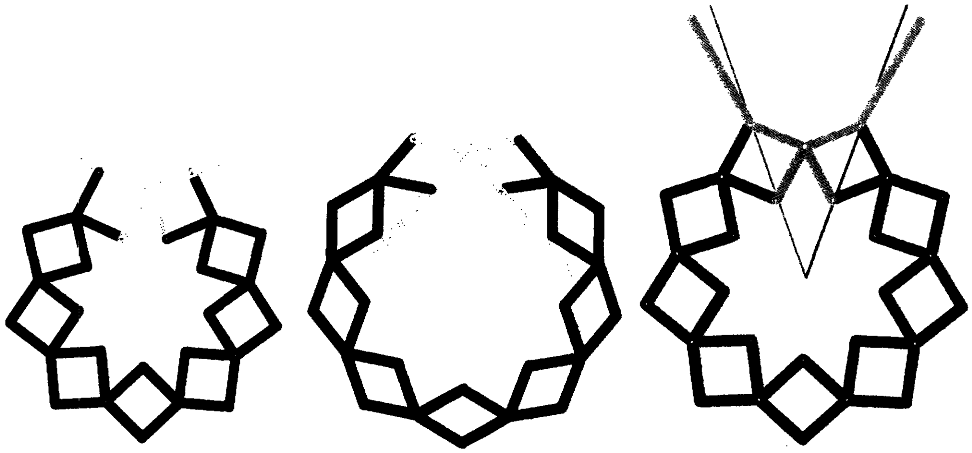


Figure 41 Schematics of internal and external extended arms device acutation.

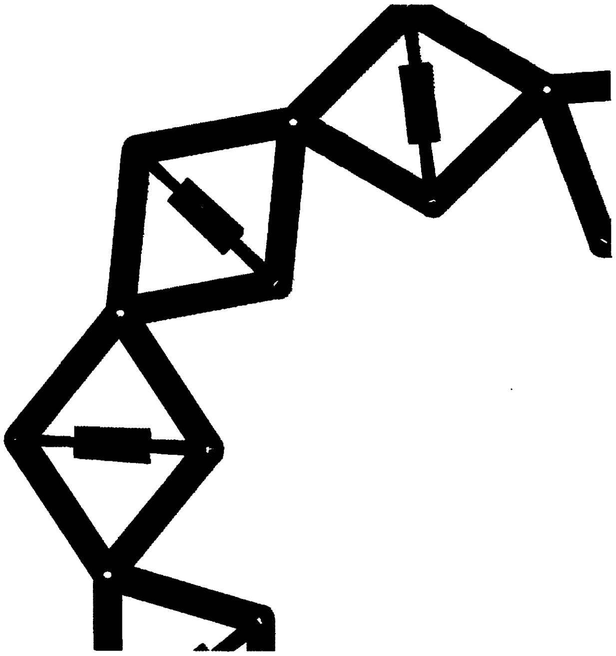


Figure 42 Detail of a piston-actuated deployment method.

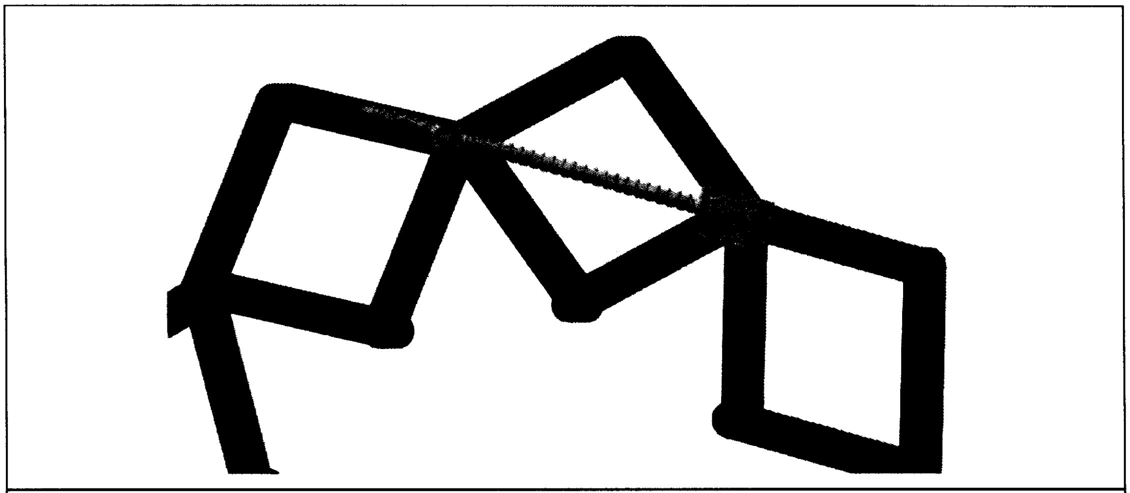


Figure 43 Detail of threaded-rod actuated device.

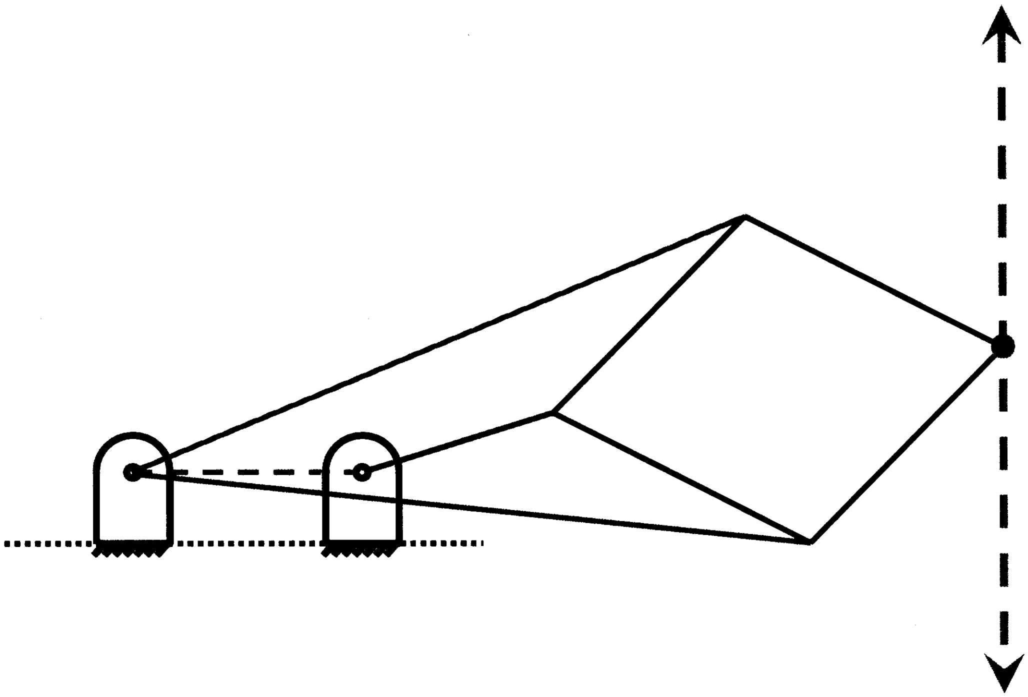


Figure 44 Peaucellier-Lipkin linkage schematic.
The members of the same color are the same length.

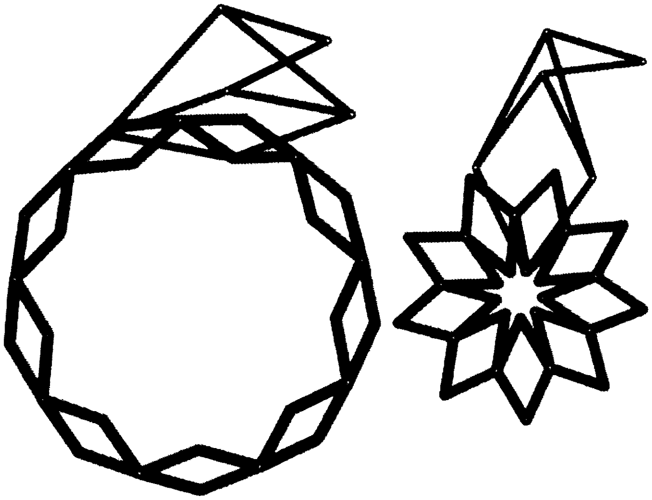


Figure 45 Externally place Peaucellier-Lipkin linkage.

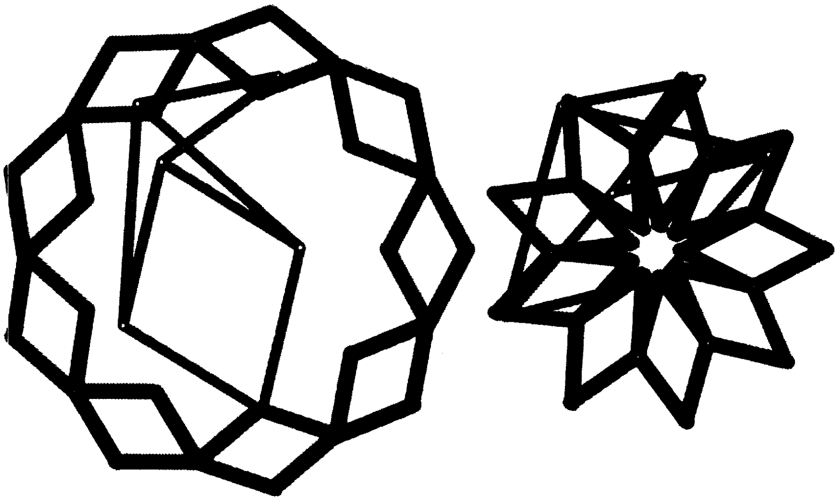


Figure 46 Internally place Peaucellier-Lipkin linkage.