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CYLINDRICAL DEVELOPABLE MECHANISMS FOR MINIMALLY INVASIVE SURGICAL INSTRUMENTS

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ABSTRACT

Developable mechanisms conform to and emerge from developable, or specially curved, surfaces. The cylindrical developable mechanism can have applications in many industries due to the popularity of cylindrical or tube-based devices. Laparoscopic surgical devices in particular are widely composed of instruments attached at the proximal end of a cylindrical shaft. In this paper, properties of cylindrical developable mechanisms are discussed, including their behaviors, characteristics, and potential functions. One method for designing cylindrical developable mechanisms is discussed. Two example developable surgical devices that exemplify these behaviors, characteristics, and functions, along with the kinematic mechanisms comprising them, are discussed in detail.

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Introduction

Medical devices have been produced and developed for millennia, and improvements continue to be made as new technologies are adapted into the field. Developable mechanisms, which are mechanisms that conform to or emerge from certain curved surfaces, were recently introduced as a new mechanism class [1]. These mechanisms have unique behaviors that are achieved via simple motions and actuation methods. These properties may enable developable mechanisms to create novel hyper-compact medical devices. In this paper we discuss the behaviors, characteristics, and available functions of cylindrical developable mechanisms, review a design process for adapting these mechanisms to medical devices, and review two example minimally invasive surgical device designs.

1 Background

Foundational work leading to this research followed a relatively linear path: first compliant, or flexible, mechanisms were developed [2], then they were created out of flat surfaces

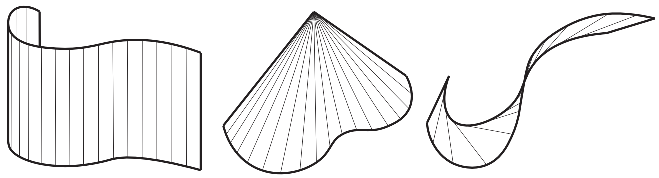

Figure 1: Three types of developable surface classes. Generalized cylinder, generalized cone, and tangent developable.

with motion that emerges from the plane (these mechanisms are called lamina emergent mechanisms, or LEMs [3, 4]. Arrays of compliant lamina emergent joints were then used to create developable surfaces from rigid materials, including curved-fold origami models [5, 6]. This inspired the adaptation of compliant and traditional rigid mechanisms to developable surfaces to create a new mechanism class [1]. In this work, these new developable mechanisms are adapted to medical devices.

1.1 Compliant and Lamina Emergent Mechanisms

A compliant mechanism is a mechanism that transfers motion, force, or energy, and gains its mobility through the flexibility of its members [2]. They can reduce cost due to their low part count and offer increased performance, including increased precision and reliability and decreased wear, weight, and maintenance. The development of analysis techniques such as the pseudo-rigid-body model [2, 7, 8] and topology optimization [9,10] have simplified analysis and allowed compliant mechanisms to become prevalent in many industries.

Lamina Emergent Mechanisms (LEMs) are mechanisms fabricated from sheet material that emerge out of plane as they actuate. LEMs can also be made fully compliant, so they can share the same advantages as compliant mechanisms. Thanks to stereolithography fabrication and the scalability of LEMs, they have enabled mechanisms and motions at the micro- and nanoscale. Examples include an on-chip nanoinjector [11] and a demonstrative belltower [12]. The initial flat state of LEMS introduces the limitation that only mechanisms with a change point can be used in their design [3]. A noteworthy LEM is the Lamina Emergent Torsional joint [13, 14], or LET joint, which provides sheet material greater flexibility in a desired location and along a desired axis.

1.2 Developable Surfaces

A developable surface can be flattened into a plane without stretching or compressing the surface. One example is ship hulls, where bending the plate material into a developable surface requires much less energy than traditional forming methods, which can require the sheet material to stretch or compress. Ushakov [15] stated the following characteristics of developable surfaces:

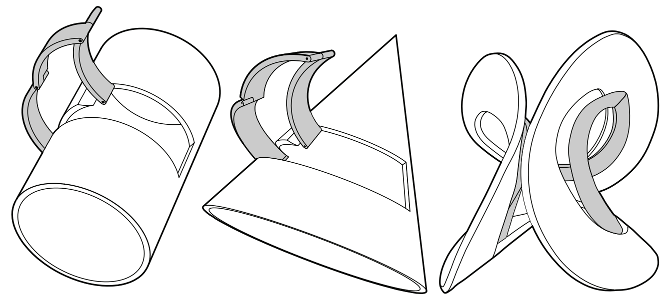

Figure 2: Three developable mechanisms. From left to right, a cylindrical developable mechanism with a planar four-bar linkage, a conical developable mechanism with a spherical four-bar linkage, and a tangent developable mechanism with a Bennett four-bar linkage.

1. They are ruled surfaces
2. They have zero gaussian curvature everywhere
3. They are isometric (do not stretch or bend when folded flat)
4. Each is an envelope of a 1-parameter family of planes

A ruling line is a straight line in space, and a ruled surface is created by sweeping a ruling line through space. In other words, through every point on a developable surface there must be a direction where a straight line can be fit to the surface. A developable surface also has zero gaussian curvature everywhere, or the product of the maximum possible and minimum possible curvatures at any point is zero. This means that the surface needs to be curved in only one direction at every point, like a cylinder. Doubly-curved surfaces have a positive or negative Gaussisan curvature, such as the sphere with positive Gaussian curvature, or the saddle with negative Gaussian curvature.

Developable surfaces are also isometric, which here means that the path length between two points on the curved surface is identical to the path length between those points when the surface is flattened. Finally, a developable surface is an envelope of a one-parameter family of planes.

Figure 1 shows the three types of developable surfaces that exist besides planes. These are generalized cylinders, generalized cones, and tangent developable surfaces. Developable surfaces can be defined by their ruling lines. In a generalized cylinder, all of the ruling lines are parallel. Generalized cones are formed when all of the ruling lines meet at a point. A tangent developable surface is formed by keeping the ruling lines tangent to any three dimensional curve [16].

1.3 Developable Mechanisms

Developable Mechanisms are a new classification of mechanism currently being researched [1]. A developable mechanism is a mechanism that conforms to or emerges from a developable surface. Lamina Emergent Mechanisms emerge from a flat plane, but they cannot be formed onto a curved surface without distortion. This can cause the mechanism to bind or change its motion and behavior. Developable mechanisms satisfy the need for mechanisms that can fit to a curved surface.

Three example developable mechanisms are illustrated in Figure 2. Developable mechanisms can be created from any developable surface by aligning the hinge axes of an applicable kinematic mechanism with the ruling lines of the surface. For example, four-bar mechanisms can be fit to a plane surface, generalized cylinder, or generalized cone [1]. Planar mechanisms map well to generalized cylinders, and spherical mechanisms map to generalized cones. The Bennett four-bar linkage and all 7R linkages, or seven-link mechanisms with revolute joints, can be fit to tangent developable surfaces. The large number of links in 7R tangent developable mechanisms creates many change points, which can make these mechanisms difficult to implement in practice. Developable mechanisms can solve a variety of problems and be fit to a wide number of applications, such as doors on a train that emerge from the curved body, wheels that have an embedded mechanism to create a walking motion, or casts and splints that quickly attach to a limb [1].

2 Properties of Cylindrical Developable Mechanisms

Here we will outline the behaviors and characteristics of cylindrical developable mechanisms and possible functions of developable medical devices to provide a guide for how to utilize these mechanisms in device creation. The Behaviors column of Figure 3 lists behaviors from classical mechanisms that are possible in cylindrical developable mechanisms. The Characteristics column lists general characteristics of developable mechanisms, and the last column shows both general functions and functions that can be derived from the specific mechanisms discussed in this paper.

2.1 Behaviors of Developable Mechanisms

Because developable mechanisms share similarities to classical kinematic mechanisms, many behaviors will also be shared with classical linkages. The major novel behavior appears when we consider the adaption of classical linkages to developable surfaces. This behavior, termed Emergent Motion, describes how the mechanisms can be designed from and move out of the material that makes up a developable surface and re-conform to that surface after actuation. The prototype in Figure 4 demonstrates how the wall of a cylinder can be cut in certain areas to allow a 4-bar mechanism to actuate, using the cylinder wall itself as linkages, but still resemble a cylinder in the closed configuration. These behaviors also exist in lamina emergent mechanisms, but important differences will be manifest as we consider the characteristics of and functions available to developable mechanisms.

Other behaviors of developable mechanisms include predictable motion (comprising the various motions described by Joskowicz [17]), energy storage, and force transfer. The behavior of energy storage exists when compliant joints are used, which also allows for the behavior of reaching multiple stable points to exist.

2.2 Characteristics of Developable Mechanisms

Nelson et al. [1] stated the following as the required criteria for a mechanism to belong to the developable mechanism class:

A developable mechanism must

1. Conform to or lie within a developable surface when both are modeled with zero thickness
2. Preserve the shape of the developable surface throughout its motion
3. Have mobility

Two of the characteristics listed in Figure 3 for developable mechanisms are comprised of the first two requirements above. These requirements also highlight the need for the axes of the mechanism joints to align with ruling lines in the developable surface, which Nelson [1] terms the joint-axis ruling condition. As a subset of criteria 1, a developable mechanism has a characteristic that allows it to be manufactured in a flat state and then curved to a developable surface state. The requirement of mobility was discussed earlier as a behavior.

When considering the connection to kinematics, developable mechanisms follow the rules and classifications of classical kinematics, which is another defining characteristic. Also, if each joint of the developable mechanism is fully compliant, it can be characterized as a monolithic mechanism.

If both criteria 1 and the joint-axis ruling condition are met, a visual or geometric characteristic emerges. These two characteristics will force the links of the mechanism to contain one or more curved surfaces. Figure 5 shows a straight-line mechanism with curved links that conform to and can be concealed within the cylindrical surface and a coupler link that partially conforms.

2.3 Functions

The collection of functions of developable mechanisms discussed here does not represent a comprehensive list, but is provided to explore the breadth of tasks these mechanisms could complete. The successful designer or engineer will use the behaviors and characteristics of developable mechanisms to design new features and find new applications in their work. Functions labeled with a "p" can be considered a processes, or a combination of functions, possibly from other non-developable surgical tools, used to perform a more detailed task. The "anchor" function can be seen in Figure 6. The mechanism shown may prevent a cylinder from rolling or may provide support for a cylindrical vehicle.

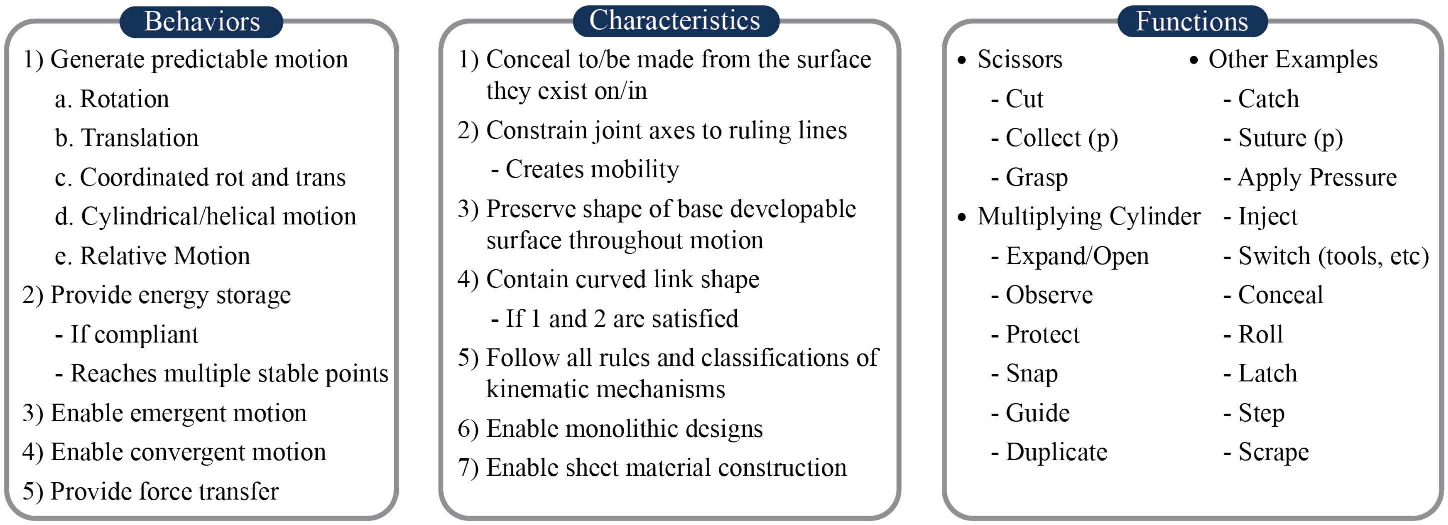

Figure 3: Behaviors and characteristics of cylindrical developable mechanisms and possible functions of developable medical devices. The functions list is not comprehensive but is included to show potential tasks. Functions marked with a (p) can be considered processes.

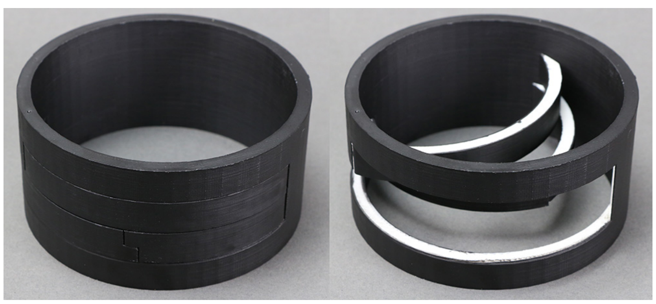

Figure 4: A prototype demonstrating emergent motion behavior. Embedded mechanisms can cleanly emerge from and conform to surfaces to preserve surface function and appearance, potentially including the water-tight behavior of solid cylinders.

Figure 5: A Roberts' straight line mechanism as a developable mechanism on a cylinder, demonstrating the conforming characteristic. The first and third links are conforming and the coupler link is partially conforming.

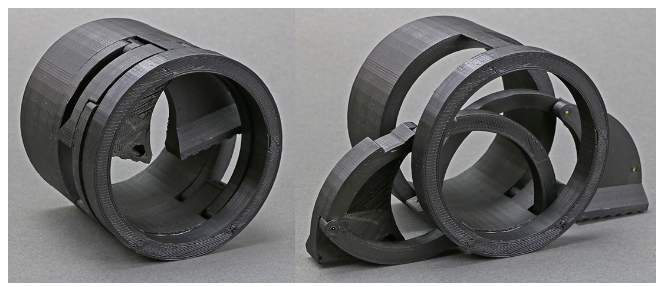

Figure 6: A prototype demonstrating the anchoring function. Feet on the coupler link could provide stability or prevent a cylinder from rolling.

3 Adaptation to Surgical Devices in Shafts

Minimally Invasive Surgery is rising in popularity because it reduces trauma on the patient compared to open surgery, which leads to less pain, decreased recovery times, and improved cosmesis [18, 19]. The tools involved in MIS are often cylindrical in shape, and the general trend is toward smaller diameter devices to further reduce pain and trauma. As the scale of these devices continues to shrink, they become more difficult to design and manufacture. Some devices have parts in the tenth of a millimeter scale. Parts in the meso-scale range are too large to be created via micro-manufacturing processes and too small for conventional machining, like milling and CNC machines. Therefore, a low part count and low design complexity are important to maintain feasibility in manufacturing. Current MIS shafts often allow only one tool to operate at the distal end, especially when the shaft diameter is small.

Developable mechanisms can address some of these issues and therefore positively impact the cost, speed, and recovery times associated with MIS. These mechanisms can create relatively simple devices with low part counts, yet provide a net increase in functionality to existing tools. The increase in functionality occurs because of their conforming nature: developable mechanisms provide the opportunity to combine devices (and therefore functions) into a single MIS tool with only a small increase in complexity. A developable instrument could be included within the walls of a cylindrical shaft and enter a workspace through a single entrance in combination with another instrument on the end of the shaft. This combination has the potential to:

1. Lower the time required to perform a task in a confined/remote workspace by reducing the number of tooling changes required.
2. Reduce the trauma/damage to the boundary of the workspace by reducing the number of entrance holes/points required.
3. Reduce the complexity of the control system used in conjunction with the tooling setup, because fewer shafts would be required to enter the space.
4. Reduce the cost of the procedure.

For example, an existing MIS tool could operate at the end of a shaft in conjunction with a developable mechanism tool that actuates outward from the cylinder (extramobile mechanism), or intermittently with a developable tool that actuates inside the cylinder (intramobile mechanism) [20].

3.1 Modeling

Each of the three developable mechanism property categories (behaviors, characteristics, and functions) can be associated with specific design processes.

1. Behaviors - Energy and Motion Modeling
2. Characteristics - Geometry and Manufacturing Options
3. Functions - Link Shape

Various modeling techniques exist that enable creation of the behaviors required to achieve a certain design or function. If a bistable design is desired, an energy analysis [21] or an established bistable design process [22] could be utilized to create a bistable compliant mechanism. If a specific motion behavior is desired, such as translation or cylindrical motion, then kinematic position, motion, or path generation modeling could be used to create it.

The characteristics category aids in the construction and geometric design of the modeled mechanism. During analytic modeling, the first three characteristics must be complied with to ensure that the finished mechanism will be developable when it is constructed. The optional characteristics, monolithic design and sheet material construction, inform the designer of different geometric design options available. For example, if a specific four-bar has been designed using path generation, the characteristics section informs us that the design can be made monolithic or be constructed from sheet material. If proper compliant mechanism design is used, the adaption to a monolithic structure or sheet material construction will not alter the path generation analysis.

As discussed in [3], lamina emergent mechanisms must be change point mechanisms to lie in a plane at some point in their motion. However, this restriction does not apply to developable mechanisms initially constructed from sheet material. As the sheet is rolled or shaped into a developable surface, the distance between links changes, potentially changing the mechanism classification. Therefore, sheet material can be used to create any developable mechanism without the change point mechanism restriction.

The function category of developable mechanism properties is where the shape of the links can be altered to accomplish the specific task desired. Because link shape in a kinematic mechanism is independent of the mechanism's motion, we can alter the shape of the links in a developable mechanism as the last stage of the design process. For example, extending a link beyond the connecting joint and thinning it down to a point can enable that link to act as a needle to perform the function of "injecting."

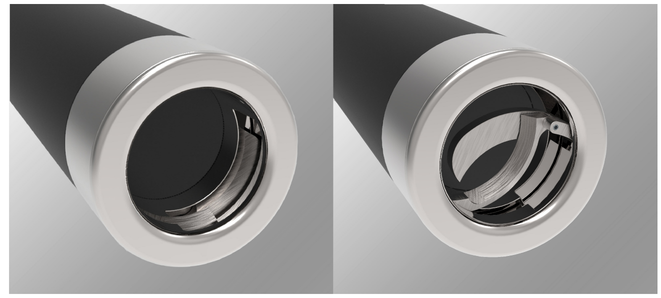

Figure 7: Rendering of an Internal Scissors design embedded in a shaft.

4 Examples

During the course of this research, multiple minimally invasive surgical devices were developed. We will explore two exemplary designs and discuss the path through the design guide that can be traced to create these devices.

4.1 Internal Scissors

The first design presented is an internal scissor mechanism, seen in Figure 7. A triple rocker four-bar mechanism is the basis for this device, with link ratios of 1:0.7368:1.289:0.5263, where the first link is ground. The curved blades of the scissors are shaped from the links, with the shortest link having a large extension beyond the hinge to create one of the blades (see Fig. 8.)

A kinematic model of this device is shown in Figure 8. Note that the ground link from the kinematic model is not physically present in the prototypes. The scissor mechanism is actuated by rotating an internal cylinder (blue) with respect to an outer cylinder (dashed line, or black cylinder in the prototype). Rotating the inner blue cylinder is equivalent to actuating a virtual link that is pinned at the center of the concentric cylinders. The ground link is therefore a virtual link connecting this center-pinned link and the orange link.

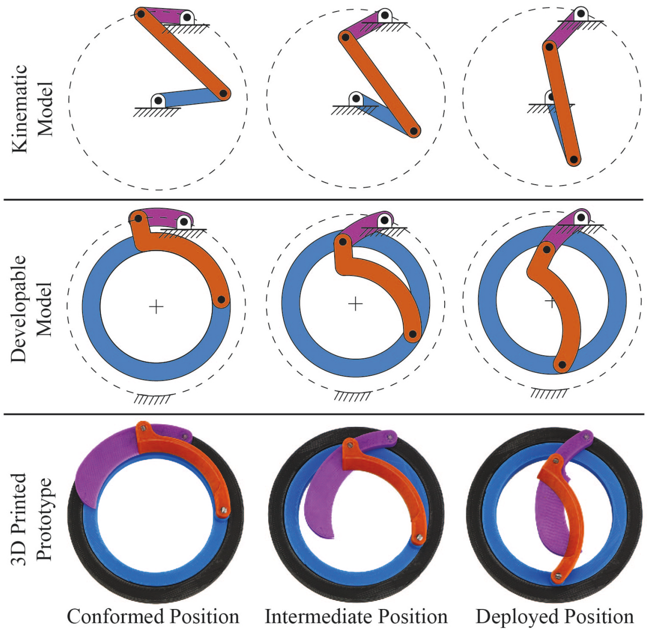

Figure 8: Kinematic skeleton diagram model of the scissors mechanism, the developable mechanism version, and a 3D-printed prototype with altered link shapes. Note: The ground link is not physically present in the prototype, and blue link is the inner cylinder, actuated by rotating with respect to the outer cylinder.

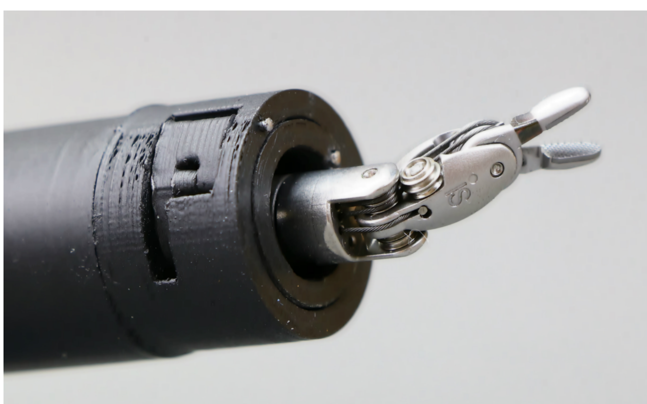

Figure 9: A 3D-printed internal scissors prototype with a forceps tool inserted.

An example of where this device could be used is in a biopsy procedure. This tool, with a forceps tool inserted in the shaft, could enter into a body cavity, grip a piece of tissue, retract it partially into the tube, and then actuate the developable tool to cut off and contain a biopsy sample of the tissue. Figure 9 illustrates this configuration.

During the design process, multiple developable mechanism properties from the design guide were used to create the internal scissors mechanism. For the initial concept to be properly designed, the relative motion and convergent motion behaviors need to be incorporated. Relative motion between two adjacent links, afterwards shaped into blades, would allow scissor-like motion. Convergent motion, or the ability for the mechanism to form back to the surface after actuation, would allow the center of the cylindrical shaft to remain completely open after the scissors were used. If the mechanism conformed to the rules of a developable mechanism, namely Characteristic 1, then the scissors would conform to the cylinder walls and allow another device to pass through the center. After modeling these behaviors and characteristics, shaping the links 2 and 3 of the mechanism into blades enables the cutting function initially desired.

4.2 Multiplying Cylinder

The second design presented here is called the "multiplying cylinder" (Figure 10). The mechanism is a triple rocker with link ratios 1:0.7368:1.289:0.5263, where the first link is ground, or the cylinder wall. The design shown in Fig. 11 has links shaped to hold LEDs. In the latest prototypes, bistability was achieved using the design technique presented by Jensen and Howell [22], resulting in the inclusion of a compliant joint between links 2 and 3.

A kinematic model of a single multiplying cylinder mechanism is shown in Figure 10. The orange link spans 180 degrees of the cylinder to potentially allow for different cylindrical, disk-shaped, or spherical tools to be affixed to or snapped into this link and be deployed outside the cylindrical shaft as the mechanism actuates. Again, only two of the four modeled links are physically present in the prototype, because the curved slider and the ground link are virtually pinned at the center of the cylinder.

The potential applications of this device are numerous. The ability to conceal and deploy multiple lines or tools from the same shaft opens new possibilities for simplifying surgical procedures. As shown in Figure 11, placing two of these mechanisms on a shaft can allow for two light or imaging devices to accompany a conventional MIS tool acting through the cylindrical shaft. The use of two cameras could enable stereoscopic vision with a larger depth of field than conventional 3D laparoscopic cameras due to the additional space between lenses. A light, camera, and forceps could be placed on one shaft, allowing the appendectomy procedure rendered in Figure 12 to be performed with two tools instead of three, while moving the image and light source to a point-of-view position on the forceps.

The multiplying cylinder development process also involved drawing several properties from the developable mechanism design guide. The initial idea behind the concept was to create secondary working channels, so the emergent motion behavior would need to be maximized to create the largest possible working channel. It was also initially desired for the mechanism to be bistable, with stable equilibrium positions at the deployed and stowed positions. This required the energy storage behavior, resulting in the included compliant member.

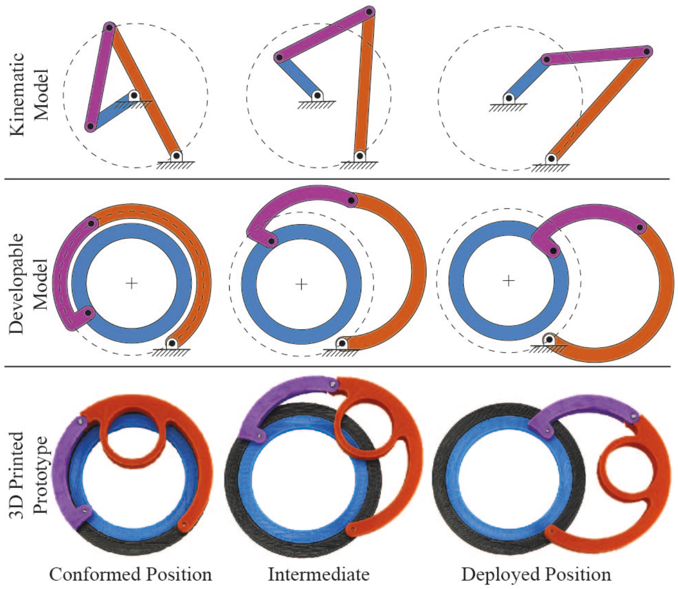

Figure 10: Kinematic skeleton diagram model of the multiplying cylinder mechanism, the developable mechanism version, and a 3D-printed prototype with altered link shapes.

Figure 11: Multiplying Cylinders mechanism with ISI forceps inserted. LED lights included to demonstrate potential application as a dual-source flashlight or a vehicle for stereoscopic vision cameras.

A monolithic design would be desirable for a multiplying cylinder placed at the end of a working shaft. This would aid in making the device disposable or interchangeable if it holds or channels one-time-use tools. The amount of functions available with the multiplying cylinder highlights its adaptability. While this is not a comprehensive list, this device was designed to perform expanding, observing (with the use of embedded cameras), snapping (bistable), guiding, protecting, and duplicating or multiplying functions. The lengthened multiplying shafts in Figure 13 could be used to perform the multiplying, guiding, and protecting functions.

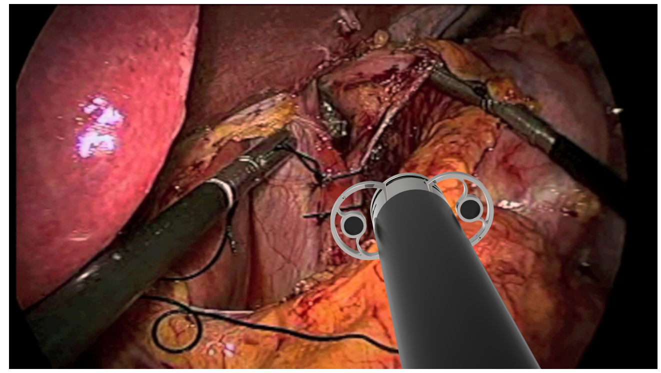

Figure 12: Rendering of multiplying cylinder superimposed on open source image from MIS appendectomy procedure.

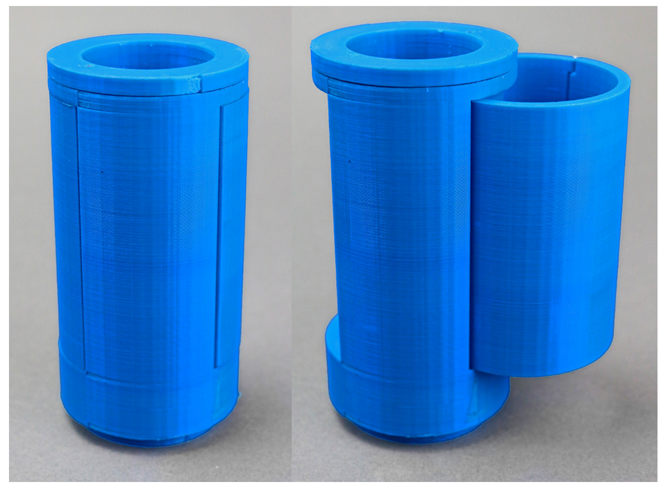

Figure 13: Secondary channel created when an elongated version of the multiplying cylinder mechanism is opened.

5 Conclusion

Developable Mechanisms, or mechanisms fit to developable surfaces, are useful because they increase the functionality of already existing surfaces by embedding deployable, concealable mechanisms on or beneath the surface. Here we have outlined these mechanisms' behaviors, characteristics, and potential functions, which can assist engineers in adapting developable mechanisms into their design work. Two cylindrical developable mechanisms, aimed at providing functionality in minimally invasive surgical procedures, have been discussed. These include the internal scissors mechanism, which could cut or grip objects inside a minimally invasive tube, and the multiplying cylinders mechanism. The multiplying cylinders was demonstrated in two configurations, one that deploys two additional stationary tools from one minimally invasive shaft, and a second that turns one cylindrical shaft into two functional working channels.

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REFERENCES

[1] Nelson, T., Zimmerman, T., Magleby, S., and Howell, L., 2019. "Developable mechanisms on developable surfaces". *Science Robotics*.

[2] Howell, L. L., and Midha, A., 1994. "A method for the design of compliant mechanisms with small-length flexural pivots". *J. Mechanical Design,* **116**(1), pp. 280–290.

[3] Jacobsen, J. O., Winder, B. G., Howell, L. L., and Magleby, S. P., 2010. "Lamina emergent mechanisms and their basic elements". *J. Mechanisms Robotics,* **2**(1).

[4] Aflattani, R., and Lusk, C., 2018. "A lamina-emergent frustrum using a bistable collapsible compliant mechanism". *Journal of Mechanism Design,* **140**(12).

[5] Nelson, T. G., Lang, R. J., Pehrson, N. A., Magleby, S. P., and Howell, L. L., 2016. "Facilitating deployable mechanisms and structures via developable lamina emergent arrays". *Journal of Mechanisms and Robotics,* **8**.

[6] Rabinovich, M., Hoffmann, T., and Sorkine-Hornung, O., 2018. "Discrete geodesic nets for modeling developable surfaces". *ACM Transactions on Graphics,* **37**(2).

[7] Megaro, V., Zehnder, J., Bächer, M., Coros, S., Gross, M. H., and Thomaszewski, B., 2017. "A computational design tool for compliant mechanisms". *ACM Transactions on Graphics,* **36**, pp. 82:1–82:12.

[8] Su, H., 2009. "A pseudorigid-body 3r model for determining large deflection of cantilever beams subject to tip loads". *J. Mechanisms Robotics,* **1**(2).

[9] Pedersen, C., Buhl, T., and Sigmund, O., 2001. "Topology synthesis of large-displacement compliant mechanisms". *International Journal for Numerical Methods in Engineering,* **50**(12), pp. 2683–2705.

[10] Sigmund, O., 1997. "On the design of compliant mechanisms using topology optimization". *Mechanics of Structures and Machines,* **25**(4), pp. 493–524.

[11] Aten, Q. T., Jensen, B. D., Tamowski, S., Wilson, A. M., Howell, L. L., and Burnett, S. H., 2012. "Nanoinjection: pronuclear dna delivery using a charged lance". *Transgenic Research,* **21**(6), pp. 1279–1290.

[12] Last, M., Subramaniam, V., and Pister, K., 2012. "Out-of-plane motion of assembled microstructures using a single-mask soi process". In The 13th International Conference on Solid-State Sensors, Actuators, and Microsystems, Vol. 2, IEEE.

[13] Jacobsen, J., Chen, G., Howell, L., and Magleby, S., 2012. "Lamina emergent torsional (let) joint". *Mechanism and Machine Theory,* **56**, pp. 1–15.

[14] Xie, Z., Qiu, L., and Yang, D., 2017. "Design and analysis of outside-deployed lamina emergent joint (od-lej)". *Mechanism and Machine Theory,* **114**, pp. 111–124.

[15] Ushakov, V., 1999. "Developable surfaces in euclidean space". *J. of the Australian Mathematical Society (Series A),* **66**(3), pp. 431–437.

[16] Cleave, J. P., 1980. "The form of the tangent-developable at points of zero torsion on space curves". *Mathematical Proceedings of the Cambridge Philosophical Society,* **88**(3), p. 403–407.

[17] Joskowicz, L., 1990. "Simplification and abstraction of kinematic behavior". *Readings in qualitative reasoning about physical systems*, pp. 597–602.

[18] Jaffray, B., 2005. "Minimally invasive surgery". *Archives of disease in childhood,* **90**(5), pp. 537–542.

[19] Robinson, T., and Stiegmann, G., 2004. "Minimally invasive surgery". *Endoscopy,* **36**(01), pp. 48–51.

[20] Greenwood, J., Magleby, S. P., and Howell, L. L., 2019. An approach for designing developable mechanisms on regular cylindrical surfaces. In review.

[21] Hanna, B., Lund, J., Lang, R., Magleby, S. P., and Howell, L. L., 2014. "Waterbomb base: a symmetric single-vertex bistable origami mechanism". *Smart Materials and Structures,* **23**(9).

[22] Jensen, B. D., and Howell, L. L., 2003. "Identification of compliant pseudo-rigid-body four-link mechanism configurations resulting in bistableor behav". *Journal of Mechanical Design,* **125**(4), pp. 701–708.

