Design and Implementation of Origami-Inspired Biomedical Miniature Robots Through Computer Visualization and 3D Modeling

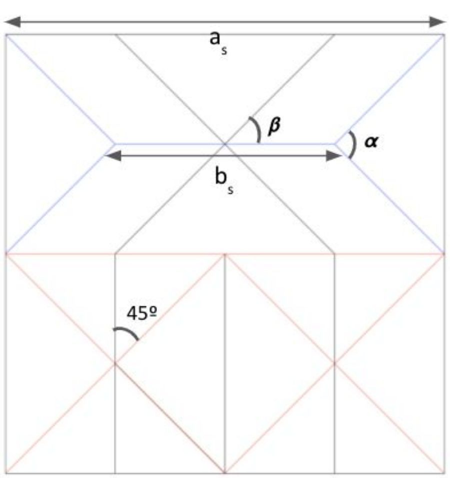
Vienna Parnell

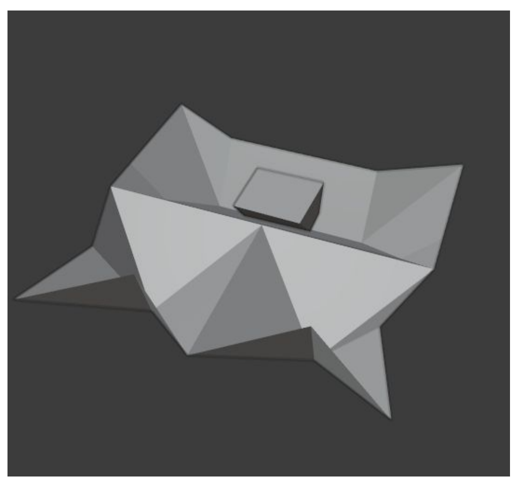
Abstract:

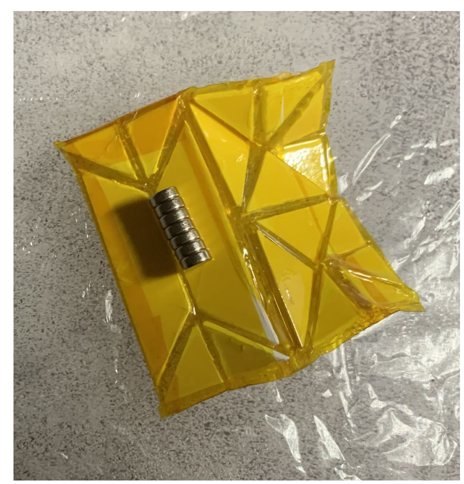
Developments in surgery have been geared toward minimizing the invasiveness of the procedure to improve both the treatment itself and the patient's postoperative wellbeing. As such, attention has been directed toward reducing human error and miniaturizing clinical devices by developing smaller devices and robotic systems. While there have already been significant advancements in this area, apparatus can further benefit from being foldable, expandable, and further condensable. By promoting these characteristics, origami engineering, which extrapolates paper-folding fundamental principles to real-world projects, has become increasingly prevalent in the biomedical field. This study is focused on the systematic understanding, design, and implementation of various origami-inspired miniature robotic components and their structure-related properties through computer visualization and 3D modeling. In addition, this study consists of experiments that fabricate and test both the system-level and component-level capabilities of the biodegradable origami-inspired miniature robotic structure. The results successfully demonstrate the miniature robot's ability to fulfill a full life-cycle, consisting of three distinct stages: self-deployment, locomotion, and degradation. Moreover, this study also tested the miniature robot in a simulated biomedical setting. The accomplishment of my research indicates potential applications in the biomedical field, including in gastrointestinal operations.

Published Origami Engineering Review Paper: http://nanobe.org/Data/View/716

Citation: Vienna Parnell, Self-Folding Non-Invasive Miniature Robots: Progress and Trend in the Biomedical Field. Nano Biomed. Eng., 2021, 13(4): 329-343. doi: 10.5101/nbe.v13i4.p329-343.







Research Background

Motivation

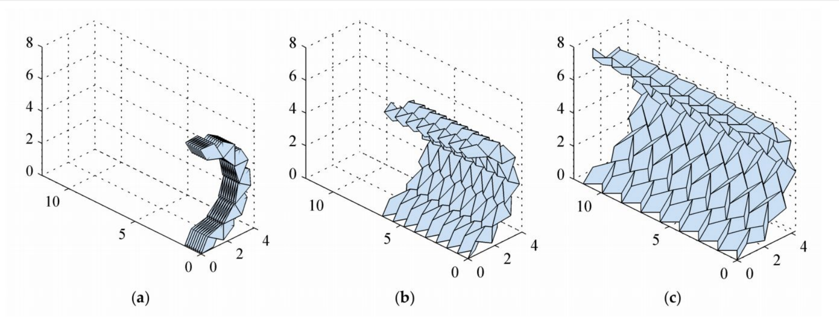
- Advancements in surgery have resulted in increasingly autonomous and miniaturized apparatus. As a result, condensed robotic components have become progressively relevant in the biomedical field, diffusing across a wide range of surgical operations [Mack, 2001].
- In more recent years, origami engineering has emerged as a potential approach in redeveloping current medical procedures. This field extrapolates the properties of developability, scalability, rigid-foldability, and flat-foldability from traditional paper folding to engineering projects [Li, 2018].
- When applied to current approaches in minimally invasive surgery (MIS), origami has the potential to revolutionize the biomedical industry by proposing even safer and more effective alternatives to current procedures [Nelson, 2010].

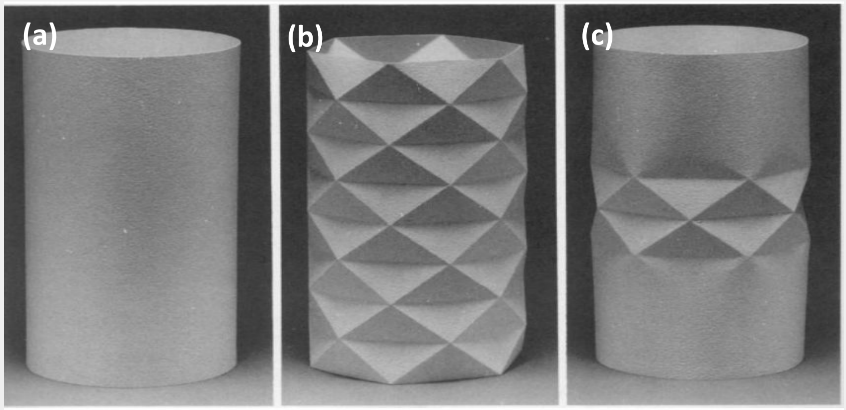
Significance

- Many patients experience the adverse effects of traditional surgeries, which entail the interference of surgeons and invasive medical devices when operating on a patient. Such procedures frequently result in perioperative complications, prolonged recoveries, and visible scarring [Jones, et al., 2001]. These impediments, however, are greatly mitigated when doctors implement MIS, which requires few to no incisions.
- While consideration of origami engineering in the biomedical field has increased in prevalence in recent years, there is a lack of systematic approach in the preliminary design process, especially without software involved. Furthermore, current research does not fully explore the versatility of materials, especially those that are more suitable for specific biomedical applications.

Engineering Goals

1. **Investigate** the methodology behind designing and fabricating miniature origami-inspired and explore a novel method to designing origami structures through computer visualization and 3D modeling.
2. Fabricate preliminary models of prototypes to demonstrate the possibility of performing several functions, including self-configuration and locomotion.
3. Study and find suitable materials that are both biocompatible and safely dissolvable for biomedical applications.





Images courtesy of the International Journal of Pure and Applied Mathematics and the Journal of Spacecraft and Rockets.

Literature Review: Summary of My Review Paper

My Review Article: "Self-Folding Non-Invasive Miniature Robots: Progress and Trend in the Biomedical Field"

Published in Volume 13, Issue 4 (2021) of *Nano Biomedicine and Engineering*

Biomedical Origami Engineering

The art of "paper-folding," commonly known as 'origami,' produces several useful mechanical and geometric properties that can be extrapolated from conventional origami art design to engineering projects (Table 1). Origami-inspired biomedical devices are currently on the rise, given their ability to adopt a compact form to function in constrained spaces, perform non-invasive procedures, and transport substances. Current applications being explored range according to their targeted area and function (Figure 1) [Johnson, 2017]. More specifically, origami-inspired clinical miniature robots have risen in prevalence tremendously over the past five years (Table 2), though while their size allows for less invasive treatment, it also places limitations on possible actuation mechanisms [Koleoso, 2020].

Table 1

Fundamental Properties of Conventional Origami Art

Characteristic	Description	Significance
Developability	A three-dimensional origami structure can be developed by folding a two-dimensional sheet [10].	Origami structures are restricted to suitable materials, depending on the application.
Flat-foldability	Origami structure can be folded into a flat configuration with its ultimate thickness depending on the material. For a vertex to be considered flat-foldable, it has to fulfill the following conditions [5]: 1. Kawasaki's Theorem dictates that the total sum of the even alternating angles is equal to the total sum of the odd alternating angles [5]. 2. Maekawa's Theorem states that the difference between the number of mountains and valleys is two [5].	The structure can occupy a compact volume while maintaining a constant surface area.
Rigid-foldability	Origami structure can fold continuously along predefined hinges without introducing facet deformations. Including additional joints increases the degrees of freedom [5], [10].	The structure can adopt a rigid, corrugated form while maintaining its flexibility and strength.

Table 2

Origami-Inspired Miniature Robot Designs With Clinical Applications in Microsurgery

Device	Material	Size	Applications	Actuation	References	Figures
Microgripper	Polymer and bimetallic layers	700μm (open) 190μm (closed)	Biopsy Cancer therapy	Biochemical and thermal actuation	Leong, et al. (2009) [42]	(Fig. 3)
Encapsulation robot	Polystyrene and PVC film	1.7 cm x 1.7 cm	Material delivery	Global heating and magnetic field	Miyashita, et al. (2015) [46]	(Fig. 4)
Gastrointestinal robot	Dried pig intestine and ice capsule	15 mm x 30 mm x 5 mm	Battery removal	Central magnet	Miyashita, et al. (2016) [47]	(Fig. 5)
Teleoperated manipulator	Piezoelectric ceramic	50 mm x 70 mm x 50 mm	Microsurgery	Three linear actuators	Suzuki & Wood (2020) [44]	(Fig. 6)
Miniature Delta robot	Polyimide film	15 mm x 15 mm x 20 mm	Microsurgery	Piezoelectric actuators	McClintock & Wood (2020) [45]	(Fig. 7)

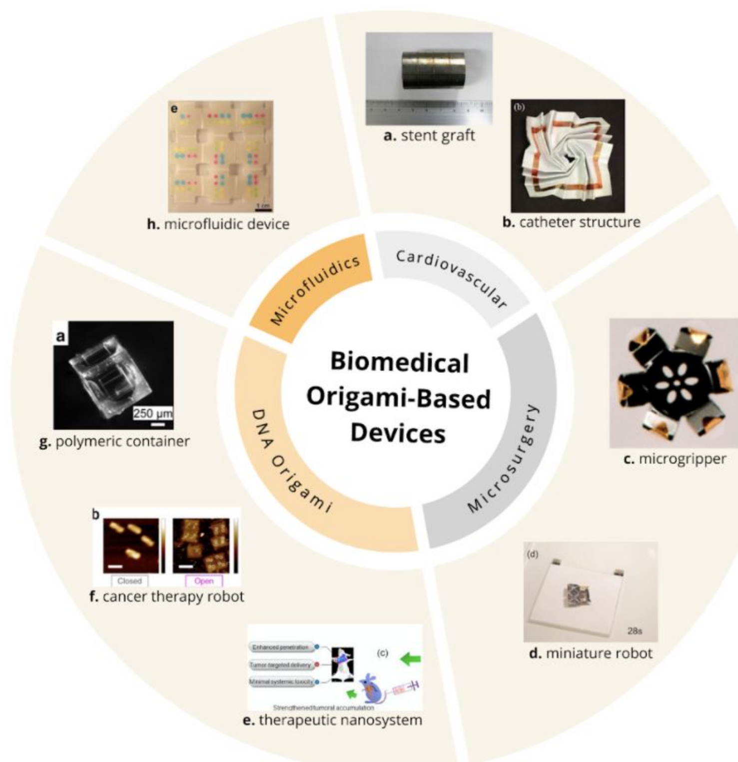
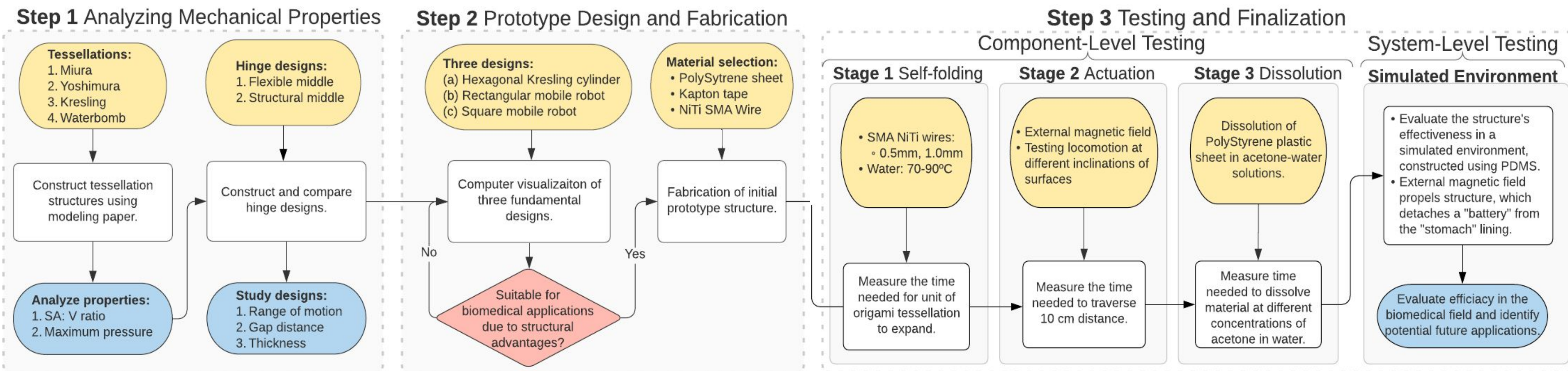


Figure 1: Biomedical origami-based devices in microfluidic, cardiovascular, microsurgical, and nanoscopic DNA origami applications. (a) Stent graft [19] (b) Catheter structure [20] (c) Microgripper [43] (d) Self-folding miniature robot [46] (e) DNA origami nanosystem [24] (f) Nanorobot [26] (g) Self-folding polymeric container [23].

Process Flow: Design, Fabrication, and Implementation

Advantages of My Novel Systematic Three-Stage Engineering-Oriented Approach

Origami structures consist of two fundamental parts: the **faces** and the **creases**. In a novel approach, my research process **systematically explores each component** of an origami-inspired structure, analyzing the properties at each stage. To ensure that my design is appropriate for clinical use, my process flow also involves exploring the versatility of materials, especially those that are more suitable for specific biomedical applications. Unlike current trends in origami engineering, my research places special emphasis on the **visualization** and **three-dimensional modeling** aspects of the process as opposed to prototype development, as understanding the fundamental properties and extrapolating them to the designs are crucial to the robot's backbone.



Step 1

- Study and construct four different tessellations.
- Calculate and compare surface area to volume ratios.
- Use push-pull gauge to measure maximum pressure structure can withstand before collapsing.
- Propose two different hinge designs and compare gap distances, range of motion, and thicknesses.

Step 2

- Using computer simulation software, model three different origami-inspired designs, and compare their shapes and ranges of motion.
- Construct a basic representation of the miniature robot using PolyStyrene plastic sheet, kapton tape, and NiTi SMA wire.

Step 3

Component-level testing:

(a) **Stage 1** Self-folding: Miniature robot transfigures from a planar sheet into a three-dimensional structure when exposed to a heat source–in this case, hot water.

(b) **Stage 2** Actuation: Miniature robot is able to move with the aid of an external magnetic field.

(c) **Stage 3:** Dissolution: Miniature robot degrades into its environment.

System-level testing:

Robot is guided inside artificial organ, simulated using PDMS material and an external magnetic field.

Investigation of Origami Engineering: Geometric and Mechanical Properties

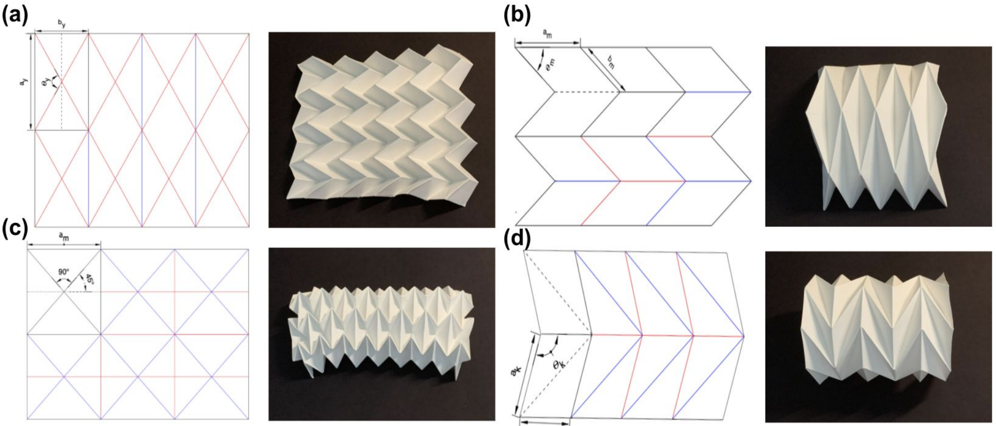


Figure 2: *Depicted above, an origami tessellation refers to a crease pattern that is repeated throughout a continuous sheet [Abtan]: a) Miura, (b) Yoshimura, (c) Waterbomb, and (d) Kresling.*

Figure 3: *Illustrated below is the procedure that measures pressure that structure can withstand before being forced into a fully compressed state. (a) Above, and (b) side views.*

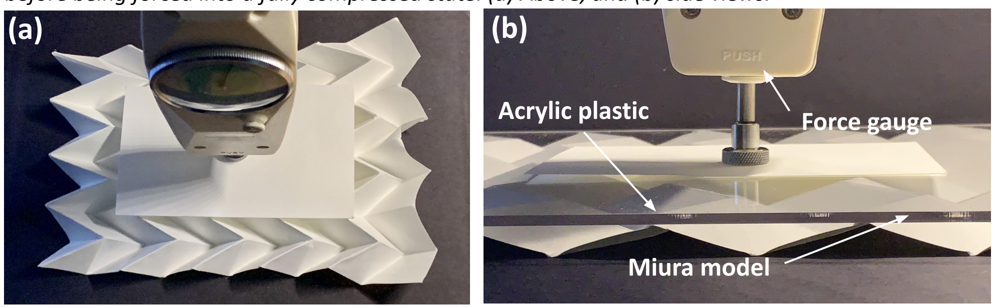


Table 3: Comparison of Origami Tessellation Structural Properties

Pattern	Overall Shape(s)	SA:V		Max P (kg/cm^2)	Figure
		Exp.	Cond.		
Miura	Cuboid	1.75	26.25	9.6	2 (a)
Yoshimura	Cylindrical	1.34	20.05	2.5	2 (b)
Kresling	Cylindrical	2.09	39.39	3.7	2 (d)
Waterbomb	Spherical, cylindrical	1.50	6.94	12.5	2 (c)

Hinge Development Process

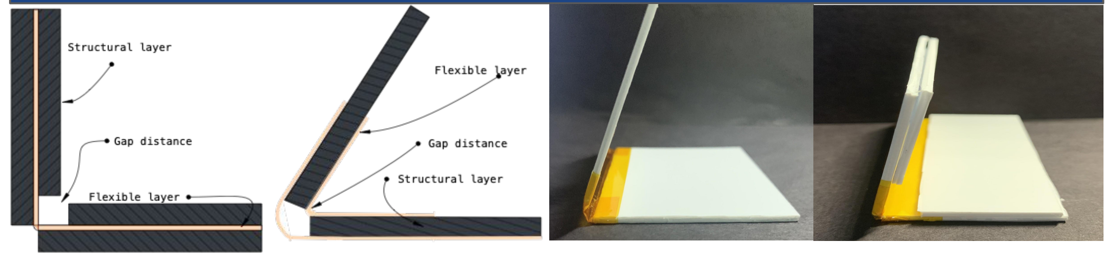


Figure 4: *Above to the left are two-dimensional hinge designs; the striped dark gray rectangles depict the structural layers, and the orange regions illustrate the flexible layers. Above to the right are their material representations: (a) Hinge design with flexible middle layer and (b) Hinge design with structural middle layer. The flexible layer is represented by kapton film, a thin, heat-resistant material. The structural layer is represented by a 1/16'' polyamide sheet, a nylon composite.*

Middle Layer	Range of motion	Gap distance (cm)	Thickness (cm)	Figure
Flexible	Bidirectional	0.5	0.4	5 (a)
		0.75	0.4	
		1	0.4	
Structural	Unidirectional	0.5	0.9	5 (b)
		0.75	0.7	
		1	0.5	

Results and Discussion: Suitable Hinge Designs

1. In the **unidirectional** design, the resulting thickness of the fold is directly proportional to the gap distance, while in the bidirectional model, the gap distance and thickness parameters are independent of each other. Thus, as the flexible-middle-layer design maintains a constant low thickness of 0.4 cm from a 0.15cm material, it is optimal for devices in minimally invasive surgical devices.
2. **Bidirectional** capabilities denote that the hinge is able to bend in either in the forward or reverse directions. This is particularly advantageous in self-folding robotic designs, as the hinge will likely benefit from both being able to condense and expand outward.

Results and Discussion: Potential Biomedical Applications Based on Experimental Findings

1. Able to withstand up to **12.5 kg/cm^2** of pressure, the **waterbomb** structure is most suitable for the microgripper and the teleoperated manipulator, as both of these biomedical applications require precise and flexible designs that can move smoothly under robotic manipulation.
2. Having the highest SA:V when both **expanded** (2.09) and **condensed** (39.39), the **Kresling** structure is especially appropriate for biomedical applications involving deployment and movement in confined areas; for instance, microsurgical encapsulation robots and drug delivery.
3. Both the **Miura** and **waterbomb** tessellations can undergo X/Y translational motion, while the **waterbomb** fold specifically can morph between cylindrical and spherical structures, designating it as particularly suitable for robotics operating in confined regions in minimally invasive surgery.

Proposed Miniature Robotic Designs: Results, Findings, and Biomedical Applications

Criteria for Rendered Designs

- Design fulfills fundamental definition of origami engineering: the three-dimensional structure originates from a two-dimensional, planar surface that undergoes folded transformations.
- **Material does not undergo stress or deformation** in simulation into three-dimensional state.
- Designs are **derived from basic tessellation designs** investigated in section on the geometry and mechanical properties of origami.
- **Actuation** and **self-folding mechanisms** are allocated specific locations in model.

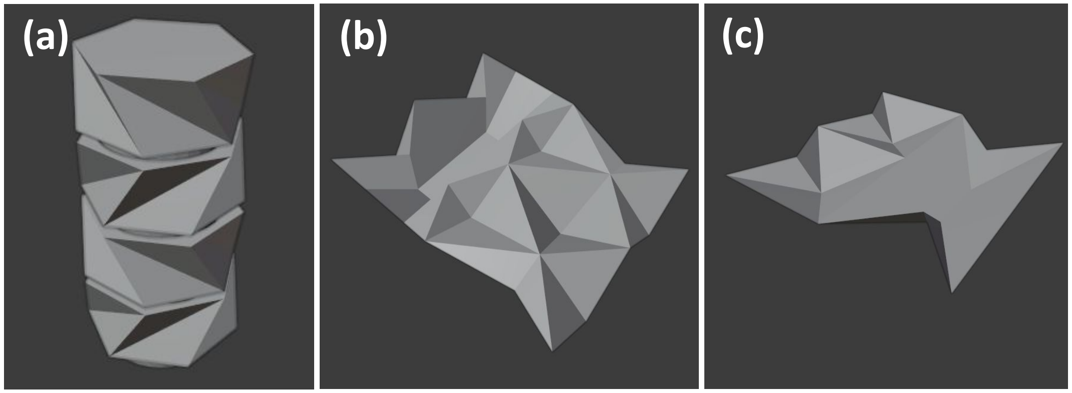


***Figure 5:** Three proposed miniature robotic designs, designed using Blender:*
(a) Hexagonal Kresling cylinder
(b) Rectangular mobile robot
(c) Square mobile robot

Discussion and Applications

- Due to its **compartmentalized** structure, **design A** benefits from the Kresling structure in that its able to expand and contract in a simultaneous motion, as opposed to designs B and C, which must systematically bend along their creases. This expedites deployment in design A though undermines its precision, making it suitable for drug delivery encapsulation.
- **Designs B and C** are similar in general shape and potential magnet placement, though the subdivision of design C allows it to fold inward into a more compact shape.
- The geometry and mechanical structure of **Design C** is explored in more detail in the next section.

	Title	Description	Actuation	Fig.
A	Hexagonal Kresling Cylinder	In its compact state, this microrobot design occupies a hexagonal shape that can be compressed along folds, oriented at 30º from the base in reverse, alternating directions. Propulsion would occur via magnetic actuation; this mechanism can be applied in improving existing biomedical microrobot designs.	Nitinol shape memory alloy spring actuators	6 (a)
B	Rectangular Mobile Robot	This robot occupies a rectangular form when not in its three-dimensional orientation. The magnetic would ideally be located near one side of the robot, allowing magnetic torque to be applied, tipping the robot in one direction and allowing for locomotion.	External magnetic field for actuation, nitinol wiring for self-folding	6 (b)
C	Square Mobile Robot	In two-dimensions, this robot occupies a square shape, though it can be folded further to be encapsulated for delivery and deployment. Similarly to the rectangular design, the magnetic would ideally be located near one side of the robot, allowing magnetic torque to be applied, tipping the robot in one direction and allowing for locomotion.	External magnetic field for actuation, nitinol wiring for self-folding	6 (c)

Self-Folding and Actuation Design: Computer Visualization

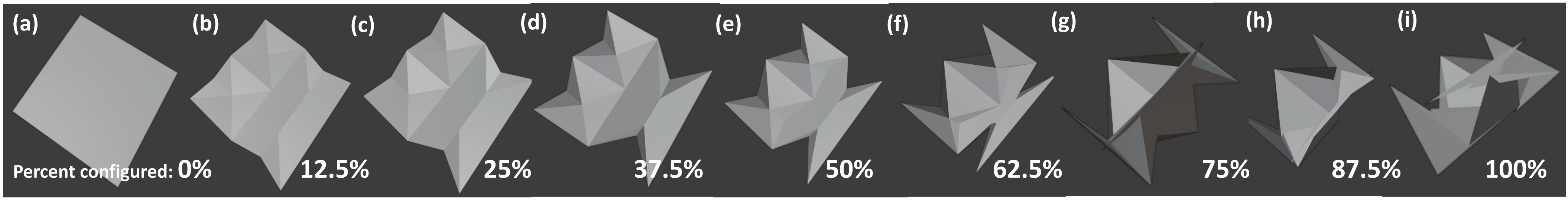


***Figure 6**: At the top, the entire process of initiation, self-folding into a structure, and deployment is divided into eight distinct stages, indicated in images (a) through (f).*

Two-Dimensional Crease Patterns and Three-Dimensional Rendering

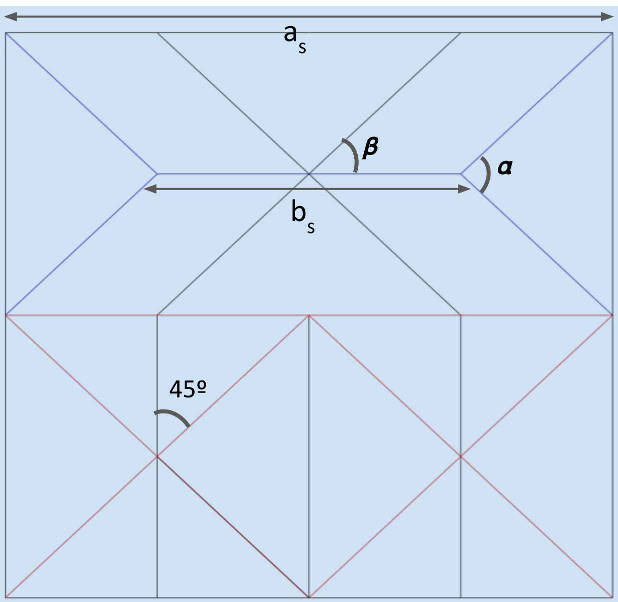
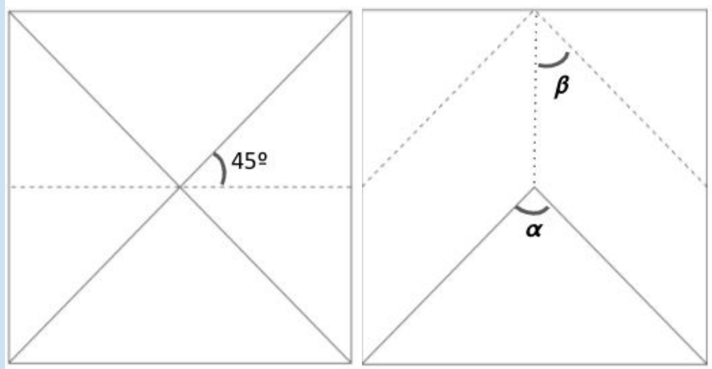


***Figure 7**: On the left, a two dimensional crease pattern is illustrated, along with the two origami tessellations that the design is derived from the Miura and the waterbomb folds. The software used was SketchUp LayOut.*



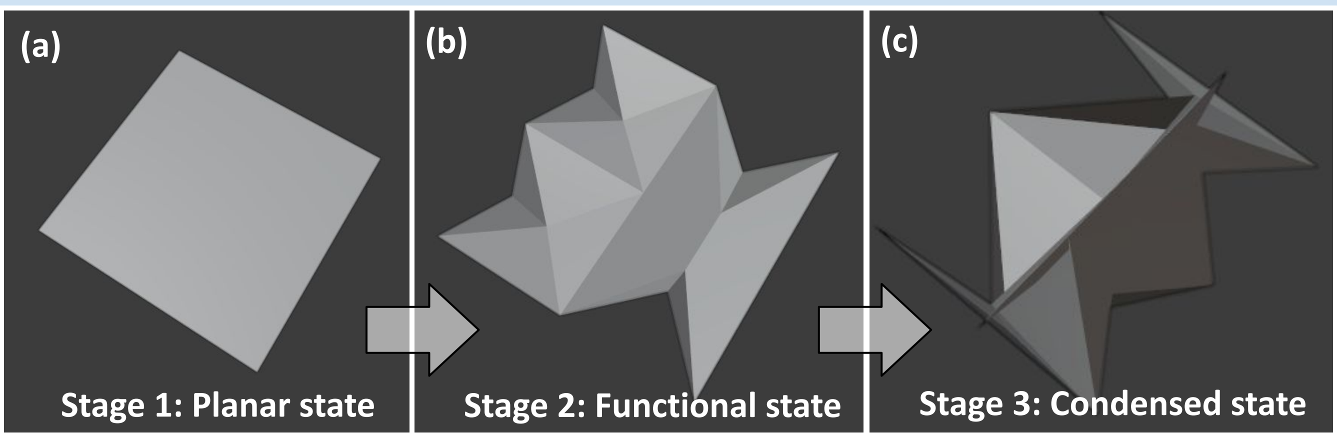


***Figure 8:** Above, a graphical depiction of the three major stages of the miniature robot in self-folding and deployment. The software used was Blender, a program used for precise animation and rendering of three-dimensional structures.*

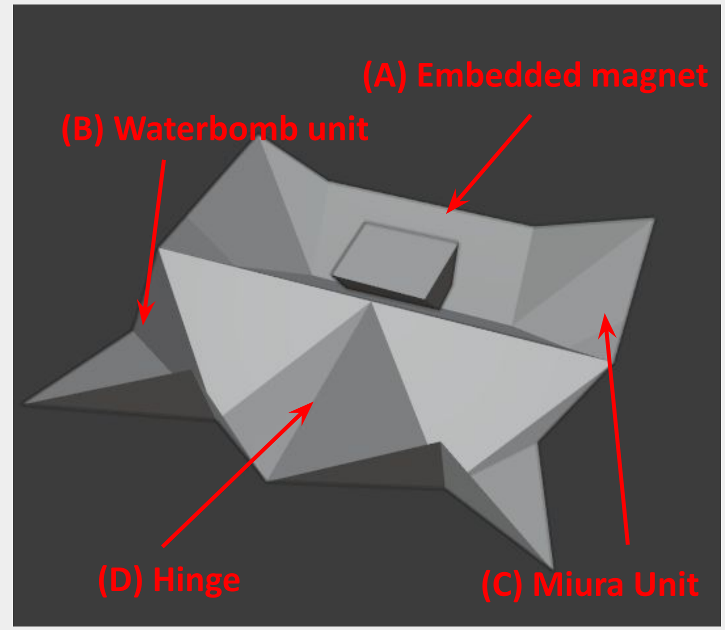
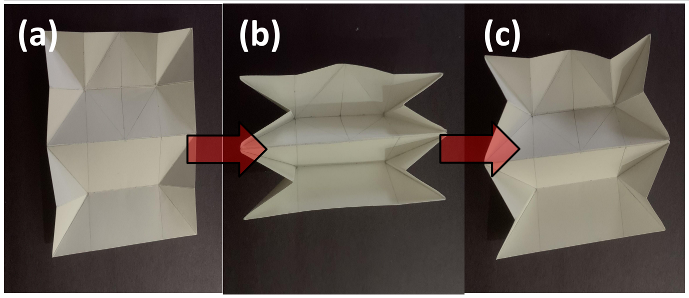


***Figure 9:** A third-POV perspective view of the complete design in its expanded form. The components are labeled as follows:*

- *(A) **Central magnet**, serving as external driving force for locomotion. The structure can be moved along a surface by manipulating this external field.*
- *(B) The region corresponding to the **Waterbomb unit** of the structure.*
- *(C) The region corresponding to the **Miura unit** of the structure.*
- *(D) Though not depicted explicitly in the diagram, each **hinge** contains Nitinol wiring; when heated or placed in warm water, the structure self-folds to the desired shape.*

Prototype: Fabrication, Implementation, and Experimentation

Square Mobile Robot's Preliminary Model, Fabrication, and Potential Biomedical Applications



To conduct component- and system-level demonstrations of an origami-inspired miniature robotic structure, I fabricated a design of C: the **square mobile robot**, with the purpose of transporting materials. The materials used were **PolyStyrene plastic** and **Kapton tape**. First, I created incisions in the hard material, representing the crease pattern of the structure. Then, I separated these sections and formed hinges joined by the flexible tape material.

Figure 10: *The above figure depicts the preliminary paper model of the origami-inspired structure. FIrst, the crease pattern was traced and folded along; then, the actual three-dimensional structure was formed. Three stages of deployment are shown: (a) In a mostly planar state, (b) in a mostly condensed state, and (c) in its approximate functional state.*

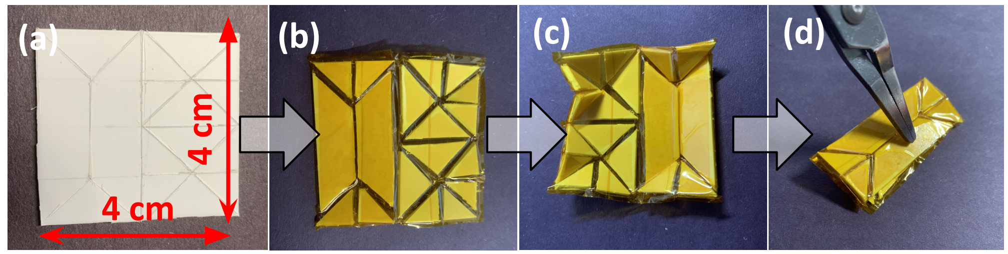


Figure 11*: (a) Etched square sheet, (b) tape-hinged structure in planar form, (c) deployed structure, (d) structure in compressed, encapsulation form*

Stage 1: Self-folding

In my component-level experimentation focused on the self-folding stage of the miniature robot, using the same methods as for the structure of the entire miniature robot, I fabricated a single unit of the waterbomb pattern for proof of concept of self-folding. I attached two strips of NiTi wiring along the central folds, and I inserted this tessellation unit into water at a temperature of approximately 80ºC. I had previously trained these two strips of wire to bend to a desired angle by heating them up over a flame, then making the wire memorize this pattern by rapidly cooling in cold water. The external heat source of the 80ºC water triggered the wires to bend inward, thus folding the flaps. I repeated this procedure for units of different dimensions and different NiTi wire thicknesses.

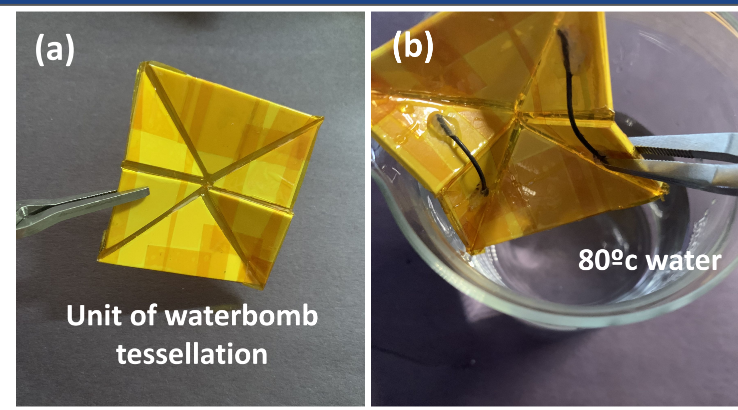


Figure 12*: (a) A plastic and tape unit of waterbomb, in planar form w/o NiTi wiring, (b) waterbomb unit in the process of self-folding along NiTi wires after exposure to heat source of approximately 80ºC water.*

Dims. (cm)	NiTi Thickness (mm)	Time to self-fold (s)
4 x 4	0.5	12.3
	1	10.4
3 x 3	0.5	10.1
	1	8.2

Discussion of Results and Relevance in Biomedical Field

Units of smaller dimensions (3 cm x 3 cm) as compared to slightly larger dimensions (4 cm x 4 cm) folded more rapidly, especially with NiTi wiring of a thicker diameter. These mechanisms would be more appropriate for robots that are functioning internally closer to the site of entrance into the body, as tasks would have to be performed more quickly due to the shorter travel time to the operating site.

Component-Level Demonstrations for Locomotion and Dissolution for Biomedical Applications

Stage 2: Translational and Rotational Locomotion of Robot Through External Magnetic Field

In the second stage of my component-level demonstrations, I evaluated the miniature robotic structure's ability to travel horizontally along a flat surface or "crawl" along an inclined slope. I attached a miniature magnet in the robot, and with the aid of an external magnetic field, I guided the robot along a distance of 10 centimeters and recorded the time taken, as well as observed its response to external resistance.

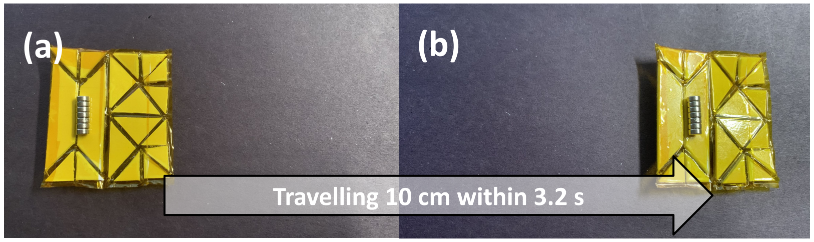


***Figure 13**: Image on the left illustrates horizontal motion of structure across a flat distance of 10 cm.*

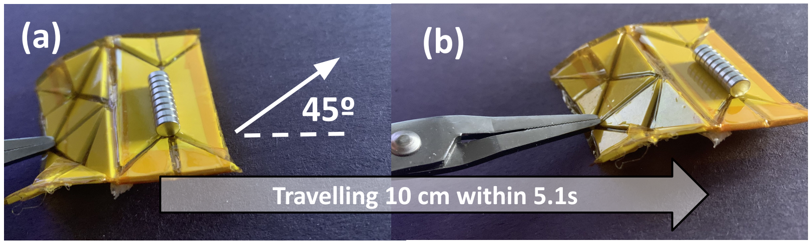


***Figure 14:** Image on the left illustrates the sloped motion of a structure across of a 45º inclined distance of 10 cm.*

Discussion of Results and Relevance in

With an external magnetic field, both miniature structures maintained their predefined three-dimensional shape while traversing the distance. Depending on the location in the body, different degrees of translation motion might be required; for instance, a gastrointestinal robot would need to travel through the esophagus and the stomach.

Motion	Time to travel 10 cm (s)	Speed = 10 cm/time (cm/s)
Horizontal	3.2	3.125
Climbing (45º)	5.1	1.961

Stage 3: Degradation of Robot into its Surroundings Through Dissolution At Different Concentrations and Temperatures

The final stage of the component-level demonstrations examined the robotic structure's ability to degrade into its environment, a feature that is crucial in clinical applications its ensuring the robot exit the body safely–in this case, the robot should be able to disintegrate almost completely.

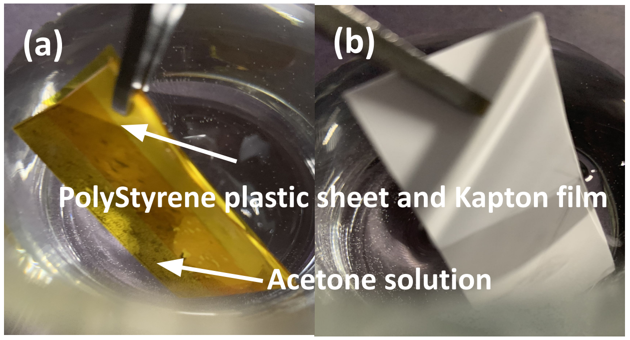


***Figure 15:** The figure to the right depicts the dissolution of a sheet of Polystyrene and Kapton film in varying concentrations of acetone solutions at different temperatures: at (a) the outside tape is still attached, and at (b) the exterior has dissolved, and the plastic itself is also in the process of disintegrating.*

Discussion of Results and Relevance in Biomedical Field

In order to ensure a more accurate and safer environment, miniature robots that are able to dissolve in lower concentrations of acidic solution are safer and more optimal. However, it must also be considered the duration of the task performed, as the robot still needs to possess enough structural integrity to perform its tasks before degrading into its environment.

% Acetone	Time to dissolve (min)
100	15:33
80	20:20
60	28:02
40	47:19

System-Level Application Demonstration in Simulated Biological Environment

Biodegradable Origami-Inspired Gastrointestinal Battery Removal: Self-Deployment, Locomotion, and Degradation

Issue Statement: A common incidence that has been rising over the past decade is the accidental ingestion of small batteries, resulting in larger complications including burns or airway blockages.

Proposed Solution: As an origami-inspired device is able to expand in confined spaces, improve the post-operative of the patient, and navigate small passages, my solution consists of implementing the square mobile robotic design in this scenario. As the battery is magnetic as well, my robotic design would be able to be swallowed, attach itself to the battery, and pull away safely.

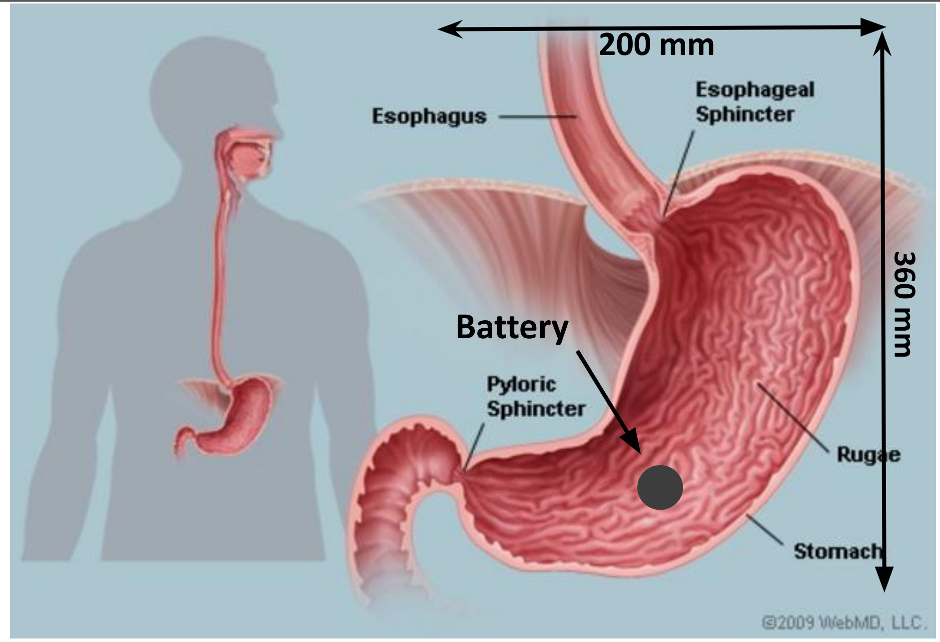


Figure 16: *The image on the right, courtesy of WebMD, illustrates the view of the digestive tract leading up to the stomach, as well as a close view of the interior of the stomach. Labels on the diagram depict the approximate dimensions of the artificial stomach environment, in addition to battery placement in the stomach lining.*

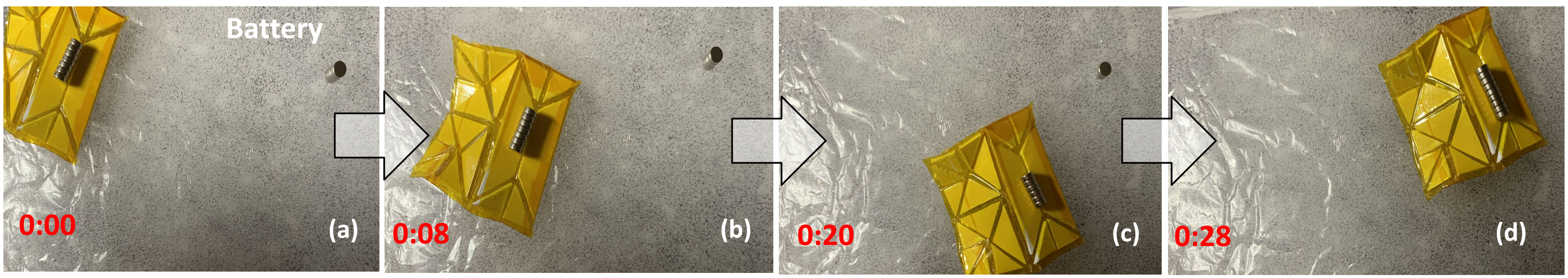


Figure 17: *The figure above depicts the traversal of the miniature robot, as propelled by an external magnetic field, along the fabricated textured PDMS sheet: (a) the robot first expands and is deployed, (b) and (c) the robot moves toward the "battery," (d) the robot attaches itself to the battery for subsequent removal from the "digestive system."*

Materials and Procedures: To simulate the surrounding textures of the human stomach, I formed a planar mold made of Polydimethylsiloxane. My experiment consisted of navigating the miniature robotic structure along artificial "channels," before guiding it to a cite containing a magnetic "battery," before dragging it away safely.

Results and Discussion: This simple demonstration highlights the potential of an expandible miniature robot structure in a specific biomedical application; without need of incisions or surgical repair, origami engineering has the potential to revolutionize approaches to common procedures.

Figure 18: *The robotic structure is diluted in an acetone solution to demonstrate proof of concept of the device completing its "full life cycle," dissolving into the environment after completing its task–in this case, removing the button battery.*

Conclusion, Potential Biomedical Applications, and Future Work

Conclusions

In conclusion, I developed a **novel, systematic approach** to origami engineering in the biomedical robotic industry. Previously, there was a lack of systematic approach in the preliminary design process, especially without software involved. My research had special **emphasis on the computer visualization and three-dimensional modeling aspects** of the process flow, as understanding the key fundamental properties and characteristics of origami engineering is crucial in successfully extrapolating them to real-world engineering projects. Most importantly, given the origami property of scalability, my preliminary design can be **replicated on several scales**. Through demonstrations on both the **system-level** and the **component-level**, my proposed design is able to accomplish the **full-life cycle** of self-folding, locomotion, and degradation in a clinical setting.

Potential Biomedical Applications

Though my research discussed a specific biomedical application in the gastrointestinal fields, miniature robotics that benefit from the valuable properties that origami engineering has to offer can be divided into four categories:

1. **Targeted therapy:** Therapies targeting specific cells and genes, for instance, drug delivery, brachytherapy, and stem cells.
2. **Material removal:** Removal of material through mechanical means, for example: ablation and biopsy
3. **Controllable structures**: Static structures with controllable positions, such as stents and scaffolds
4. **Telemetry**: Transmission of information through radio, visible light, and ultrasound

Given my robot design's size, actuation mechanism, and simplicity, the **material removal** application is most suitable. There are **two main areas** within this application that can be strongly considered:

1. **Ablation**: Using scraping or transmission to remove material from the surface of an object.
2. **Biopsy**: Also known as excision, this process involves retrieving a bodily sample for analysis either ex vivo or in situ.

Future Work

Despite being known as an ancient art not commonly associated with engineering projects, origami folding is providing **valuable insight into the biomedical field**. Implementation of origami engineering in **noninvasive microsurgery has been progressing throughout the past decade**, as evident in recent notable developments in origami-inspired microsurgical robotic systems, which improve upon their conventional counterparts by further simplifying and miniaturizing the designs. While the small-scale conditions might present a challenge and reduce the capabilities of the miniature robot, advancements in fabrication, **advancements in microfabrication methods will continue to pave the way for future applications in microsurgery**. Thus, my potential future work would be focusing on **further miniaturizing** the robotic structures and fabricating them with biocompatible and biodegradable materials, in addition to conducting system-level tests in **simulated clinical environments**.

References and Supplemental Information

References

1. Mack, M. J. (2001). Minimally Invasive and Robotic Surgery. JAMA, 285(5), 568–572. http://doi.org/10.1001/jama.285.5.568
2. Nishiyama, Yutaka. (2012). Retrieved 17 July 2020, from https://pdfs.semanticscholar.org/bf14/142cbb18c38bf92556a8880ad56d7dcea83b.pdf?_ga=2.59986477.1497851170.1594999888-262282858.1594099366
3. Schenk, Mark. et al. (2014). Review of inflatable booms for deployable space structures: packing and rigidization. Cambridge, UK. Retrieved 17 July 2020, from https://core.ac.uk/download/pdf/42337459.pdf
4. Li, et al. (2018). Architected Origami Materials: How Folding Creates Sophisticated Mechanical Properties. Advanced Materials, 31(5). https://doi.org/10.1002/adma.201805282
5. Nelson, B. J., et al. (2010). Microrobots for Minimally Invasive Medicine. Annual Review of Biomedical Engineering, 12(1), 55–85. http://doi.org/10.1146/annurev-bioeng-010510-103409
6. Jones, D., B., & Rege, R., V. (2001). Surgical Research. 573-582. http://doi.org/10.1016/B978-012655330-7/50046-0
7. Johnson, M., et al. (2017). Fabricating biomedical origami: a state-of-the-art review. International journal of computer assisted radiology and surgery, 12(11), 2023–2032. http://doi.org/10.1007/s11548-017-1545-1
8. Koleoso, et al. (2020) Micro/nanoscale magnetic robots for biomedical applications. Materials Today Bio, 8, 100085. https://doi.org/10.1016/j.mtbio.2020.100085
9. Jones, D., B., Rege, R., V. (2001). Surgical Research. doi: 10.1016/B978-012655330-7/50046-0
10. Chen, Q., Merath, K., Bagante, F., Akgul, O., Dillhoff, M., Cloyd, J., & Pawlik, T. M. (2018). A Comparison of Open and Minimally Invasive Surgery for Hepatic and Pancreatic Resections Among the Medicare Population. Journal of gastrointestinal surgery : official journal of the Society for Surgery of the Alimentary Tract, 22(12), 2088–2096. doi: 10.1007/s11605-018-3883-x
11. Rey, J., Ogata, H., Hosoe, N., Ohtsuka, K., Ogata, N., Ikeda, K., Aihara, H., Pangtay, I., Hibi, T., Kudo, S., & Tajiri, H. (2010). Feasibility of stomach exploration with a guided capsule endoscope. Endoscopy, 42 7, 541-5. doi: /10.1055/s-0030-1255521
12. Nelson, B. J., Kaliakatsos, I. K., & Abbott, J. J. (2010). Microrobots for Minimally Invasive Medicine. Annual Review of Biomedical Engineering, 12(1), 55–85. doi: 10.1146/annurev-bioeng-010510-103409
13. Turner, N., Goodwine, B., & Sen, M. (2016). A review of origami applications in mechanical engineering. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 230(14), 2345–2362. doi: 10.1177/0954406215597713
14. Wu, W., You, Z. (2011). A solution for folding rigid tall shopping bags. Proc. R. Soc. A. 467: 2561–2574. doi:10.1098/rspa.2011.0120
15. Konings, R., & Thijs, R. (2001). Foldable Containers: a New Perspective on Reducing Container-Repositioning Costs. European Journal Of Transport And Infrastructure Research, 1(4). doi:10.18757/ejtir.2001.1.4.3503
16. Cheng, N., Abraham Rodriguez and Ashley Koger. (2012) Folded Sun-Shades: from Origami to Architecture, in Digital Aptitudes, Proceedings of the 100th Annual ACSA National Meeting.
17. Nishiyama, Y. “Miura Folding: Applying Origami to Space Exploration.” International Journal of Pure and Applied Mathematics 79.2 (2012): 269-79.
18. Zhakypov, Z., Mori, K., Hosoda, K. et al. Designing minimal and scalable insect-inspired multi-locomotion millirobots. Nature 571, 381–386 (2019). https://doi-org.puffin.harker.org/10.1038/s41586-019-1388-8
19. Francis, K. (2013). Origami-Based Design for Engineering Applications. Theses and Dissertations. Brigham Young University, Provo, Utah, EE. UU. https://scholarsarchive.byu.edu/etd/3998
20. Johnson, M., Chen, Y., Hovet, S., Xu, S., Wood, B., Ren, H., Tokuda, J., & Tse, Z. (2017). Fabricating biomedical origami: a state-of-the-art review. International journal of computer assisted radiology and surgery, 12(11), 2023–2032. doi: 10.1007/s11548-017-1545-1
21. The Stomach (Human Anatomy): Picture, Function, Definition, Conditions, and More. (2929). Retrieved 11 April 2021, from https://www.webmd.com/digestive-disorders/picture-of-the-stomach
22. Fernandes, R. Gracias, David. H. (2012). Self-folding polymeric containers for encapsulation and delivery of drugs. Advanced Drug Delivery Reviews, 64(14),1579-89. doi: 10.1016/j.addr.2012.02.012
23. S. Miyashita, S. Guitron, K. Yoshida, S. Li, D. D. Damian, D. Rus, Ingestible, controllable, and degradable origami robot for patching stomach wounds, in Proceedings of the IEEE International Conference on Robotics and Automation (ICRA) (IEEE, 2016), pp. 909-916. doi: 10.1109/ICRA.2016.7487222
24. Miyashita, S., Guitron, M., Ludersdorfer, C., Sung, R., & Rus, D. (2015). An untethered miniature origami robot that self-folds, walks, swims, and degrades. 2015 IEEE International Conference on Robotics and Automation (ICRA), Seattle, WA, 2015, pp. 1490-1496, doi: 10.1109/ICRA.2015.7139386
25. Liu K, Paulino GH (2017) Nonlinear mechanics of non-rigid origami: an efficient computational approach. Proc. R. Soc. A 322 473(2206):20170348.
26. Shuhei, Miyashita. Ingestible, controllable, and degradable origami robot for patching stomach wounds.” (2020). Retrieved 23 July 2020, from https://dspace.mit.edu/bitstream/handle/1721.1/103071/201605ICRA_MiyashitaEtAl_Preprint.pdf?sequence=1&isAllowed=y
27. Hawkes, E., et al. (2010). Programmable matter by folding. Proceedings of the National Academy of Sciences of the United States of America, 107(28), 12441-12445. https://doi.org/10.1073/pnas.0914069107

Supplemental Information