Proceedings of the ASME 2019 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2019
August 18-21, 2019, Anaheim, USA

IDETC2019-98214

KINEMATIC MODELING OF ORIGAMI-BASED FORCEP DESIGNS

Dina Joy K. Abulon

Robotics and Automation Laboratory
Department of Mechanical and Aerospace Engineering
University of California
Irvine, California 92617
Email: dabulon@uci.edu

J. Michael McCarthy

Robotics and Automation Laboratory
Department of Mechanical and Aerospace Engineering
University of California
Irvine, California 92617
Email: jmmccart@uci.edu

ABSTRACT

In the design of practical grasping tools such as forceps or grippers, it may be desirable to create a compact, lightweight, and easily manufactured tool. Origami inspired designs can help simplify gripper manufacturing to a single planar sheet of material while still allowing for deployment and actuation. Inflatable structures can reduce weight and be compacted. This paper explores the design of an inflatable, deployable, action origami inspired gripper through the development of a predictive model, prototype fabrication, and preliminary design assessments.

1 INTRODUCTION

Origami-based tool designs are advantages because manufacturing can be very simple while the resulting tool can be light weight and compact. Origami is created by taking a single flat sheet of paper in its initial state, folding various creases on the sheet, then creating a three-dimensional object which is considered the final, deployed state. Two types of creases are used in origami: mountain folds and valley folds. O'Rourke defined a vertex as a point where multiple creases meet that is not not on the boundary or edge of the sheet of paper [2]. The vertex is classified by the degree or number of creases occurring at the vertex. Origami can be considered a deployable mechanism because the structures can transform from one shape to another. Some deployable mechanisms such as solar arrays or modular robots have been designed as repeated sets of 1 degree of freedom (DOF) mechanisms [3]. In addition to repeating units, a variation of origami can include a structure made of multiple layers also known as pop-up mechanisms [4]. Several studies have evaluated deployable mechanisms as planar linkage mechanisms where a large deployable structure is made of smaller 1 DOF units [5, 6, 7].

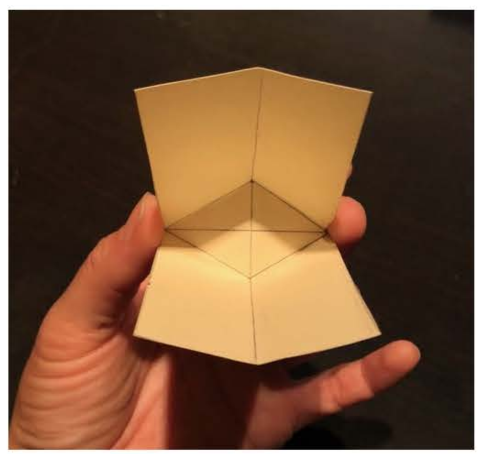

FIGURE 1. Shafer's chomper operates by folding the side vertices backwards which causes the top and bottom vertices to close toward the center [1].

While origami is the art of folding a flat sheet of paper from the initial state to a final three-dimensional (3D) state, action

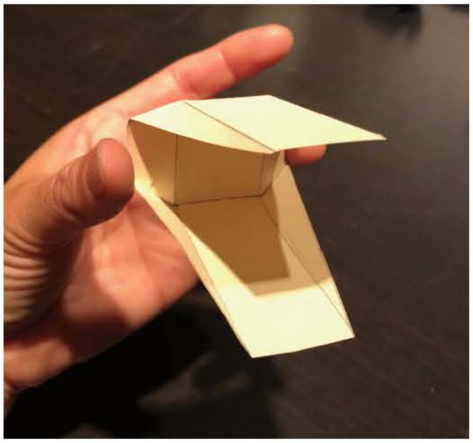

FIGURE 2. The Oriceps forceps operates by folding the side flaps backwards which causes the top and bottom flaps to close toward the center [9].

origami is a 3D structure that creates motion in its final, deployed state [8]. This subgroup of origami has also been referred to as kinematic origami where relative motion of structural elements are analyzed. One example of action origami is a sheet that has been folded to a final state of a flapping crane then repetitive pulling of the head and the tail away from each other generates a flapping motion of both wings.

A classic action origami monster mouth called Shafer's chomper can be considered the basis for a gripper design, Figure 1. As the sides of that mouth move, the top and bottom of the mouth begin to close toward each each other. Oriceps is another origami-based forcep design, Figure 2. From a single sheet of paper, the folded Oriceps configuration is able to clamp as a forcep similar to the way Shafer's chomper closes. A single input force is applied to the center panel that creates a pushing and pulling motion which causes the forceps to close and open [1]. Edmonson et al. evaluated various prototypes to optimize mechanical advantage, mechanism selection, material suitability, scalability, and stiffness [9]. Oriceps is a more complicated forcep design that has more vertices than Shafer's chomper. Both action origami structures can be created from a single sheet of paper and actuate in the final, deployed state.

Various deployable structures have been based on origami folding. The key benefit of deployable origami structures is the ability of a single sheet of material to be folded into a functional tool. In other words, deployable origami allows for simple manufacturing plus a compact-able, functional device. In one study, the prototype of a novel, 3D printed, deployable origami wheel with adjustable diameter was evaluated [10]. Similarly, various materials such as plastic, thin steel plates, and fabric were used to design deployable circular structures using zigzag folds [11]. Various folds used to compact a flat structure were assessed in another study [12]. None of the deployable structures referenced in this paragraph were inflatable.

Inflatable bladders are also used as a type of deployable structure. The benefits of inflatables are the light weight structure, compactness, and the ability to modify structural stiffness. Single and parallel-connected inflatable fabric beams for a floating causeway demonstrated that structural stiffness was dependent on internal pressure, beam cross-section, and beam length [13]. Inflatable bladders have been used in architecture of various buildings. For safety, deployable car airbags, locomotive cab interior padding and restraints, deicing bladders for truck rooftops, and tsunami airbags have all been designed and assessed [14, 15, 16]. Other deployable structures include: rigid inflatable boats, bridges, causeways, inflatable airships, space structures, and launch and recovery systems. Inflatables have also been scaled down for medical devices where a asymmetric balloon pattern was used to influence the folding pattern of a stent [17].

Some inflatable and deployable structures exhibit motion in their final state similar to action origami. One example is a portable patient lift system for assistant living homes [18]. Another study evaluated networks of inflatable tubes with different deployment methods such as: rolling, zigzag folding, modified zigzag folding, and spiral folding. [19]. One inflatable device incorporated both inflatable and deployable mechanisms with origami in an inflatable space antenna using origami zigzag folding pattern [20].

More complex inflatables such as robots have been evaluated. One mobile, hermetically-sealed, shape-changing robot was designed for exploration and penetration of narrow spaces [21]. For most inflatable robots, the rigid link of the robotic arm was replaced with a more lightweight inflatable vessel [22, 23, 24, 25]. One polyethylene inflatable robotic arm design used a non-inflatable joint structure for high positioning accuracy and used a pneumatic bag actuator for motion [24]. Similarly pouch motors were used to actuate an acrylic hand and plastic robotic arm [26, 27, 28]. In other research a multi-chamber inflatable gripper with a combination of both inflatable and rigid elements was also evaluated [29].

More exploration is needed on inflatables that exhibit motion in the final deployed state. To the authors' knowledge, no action origami based gripper comprised of various inflatable chambers with nonrigid elements has been developed or evaluated. This paper explores the novel design concept of two different action origami-inspired grippers with both inflatable, deployable, action-origami properties that allow for a compact, light weight, and easily manufactured tool for various grabbing and moving applications. Prototypes were fabricated and assessed and predictive kinematic models for the grippers were developed verify origami motion.

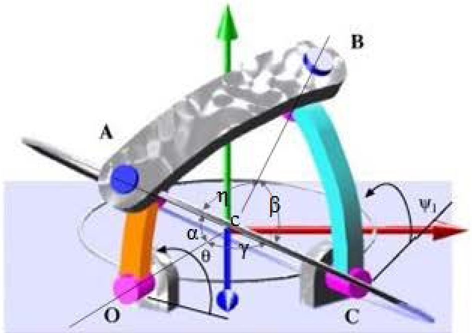

FIGURE 3. A spherical four-bar mechanism with input angle θ and output angle ψ [30]. The points **A** and **B** move on concentric spheres about the origin.

2 METHODS

Kinematic Model

In this paper, the kinematic grippers are represented by ideal rigid body models. Folds are modelled as revolute joints and facets between folds are modelled as rigid links. A single vertex in the gripper structure is modeled as a spherical mechanism and constraints around a vertex are represented by a series of matrices.

The position of the vertices are analyzed as each structure is actuated. The chomper is represented as an open chain, coupled spherical mechanism. The spherical mechanism at one vertex is modeled. Then, the spherical mechanism around the second vertex of the chomper is created by making a copy of the first vertex, translating the origin by a unit length of 1, then rotating the orientation by 180 degrees, Figure 4. The Oricep is represented as closed system, non-periodic spherical mechanism. Half of the structure is represented by modelling spherical mechanisms at two vertices. Due to the symmetry of the Oriceps structure, the motion of the the two spherical mechanisms can be mirrored to represent the full Oriceps structure, Figure 5.

Starting at one vertex of the chomper, the orientation of the spherical mechanism is defined by naming the vertex **c**. Following [30], we define the axes of **O**, **A**, **B**, and **C** of a spherical quadrilateral closed chain linkage as unit vectors originating at **c** and ending at the revolute joints of each link [9]. The ground link is **OC**, the input link is **OA**, the coupler link, **AB**, and the output link **CB**. The input angle θ is the dihedral angle that defines the rotation of the input crank around the line **cO** while the output angle ψ is the dihedral angle that defines the rotation fo the output crank about the line t**cC**, Figure 5.

The sides of the spherical four bar linkage can be defined by the angles,

$$\alpha = \arccos((\mathbf{A}-\mathbf{c})\cdot(\mathbf{O}-\mathbf{c}), \beta = \arccos((\mathbf{B}-\mathbf{c})\cdot(\mathbf{C}-\mathbf{c}),$$
$$\gamma = \arccos((\mathbf{C}-\mathbf{c})\cdot(\mathbf{O}-\mathbf{c}), \eta = \arccos((\mathbf{B}-\mathbf{c})\cdot(\mathbf{A}-\mathbf{c}). \quad (1)$$

The angular dimension η between the moving axes **A** and B of a spherical 4R linkage is constant throughout the movement of the linkage. This provides the constraint equation

$$(\mathbf{A}-\mathbf{c})\cdot(\mathrm{B}-\mathbf{c}) = \mathbf{A}_c\cdot \mathrm{B}_c = \cos\eta, \quad (2)$$

which we use to determine the output angle ψ as a function of the input angle θ.

The coordinates of **A** and **B** relative to **c** are given by

$$\mathbf{A}_c = \begin{Bmatrix}\cos\theta\sin\alpha\\ \sin\theta\sin\alpha\\ \cos\alpha\end{Bmatrix}, \mathbf{B}_c = \begin{Bmatrix}\cos\gamma\cos\psi\sin\beta+\sin\gamma\cos\beta\\ \sin\psi\sin\beta\\ -\sin\gamma\cos\psi\sin\beta+\cos\gamma\cos\beta\end{Bmatrix}. \quad (3)$$

Substitute this into (2) to obtain

$$\begin{aligned}&\cos\theta\sin\alpha(\cos\gamma\cos\psi\sin\beta+\sin\gamma\cos\beta)\\ &+\sin\theta\sin\alpha\sin\psi\sin\beta\\ &+\cos\alpha(-\sin\gamma\cos\psi\sin\beta+\cos\gamma\cos\beta) = \cos\eta, \quad (4)\end{aligned}$$

where sin and cos denote the sine and cosine functions. Collect the coefficients of $\cos\psi$ and $\sin\psi$ in this equation, so this constraint equation takes the form

$$A(\theta)\cos\psi + B(\theta)\sin\psi + C(\theta) = 0, \quad (5)$$

where

$$\begin{aligned}&A(\theta) = \cos\theta\sin\alpha\cos\gamma\sin\beta - \cos\alpha\sin\gamma\sin\beta,\\ &B(\theta) = \sin\theta\sin\alpha\sin\beta,\\ &C(\theta) = \cos\theta\sin\alpha\sin\gamma\cos\beta + \cos\alpha\cos\gamma\cos\beta - \cos\eta \quad (6)\end{aligned}$$

This equation has the solution given by

$$\psi(\theta) = \arctan\left(\frac{B}{A}\right) \pm \arccos\left(\frac{-C}{\sqrt{A^2+B^2}}\right). \quad (7)$$

Notice that there are two output angles ψ associated with each input angle θ. These result from the fact that the spherical triangle $\triangle\mathbf{ABC}$ can be assembled with **B** on either side of the diagonal **AC**. The angle $\delta = \arctan(B/A)$ locates the diagonal **AC**, and $\varepsilon = \arccos(-C/\sqrt{A^2+B^2})$ is the angle above and below this diagonal that locates the driven crank. The relationship between the input and output was calculated using Mathematica and the model for each gripper is shown in the results section.

TABLE 1. Link angular dimensions for Shafer's chomper and Edmonson's Oriceps.

Forcep design	α	η	γ	β
Chomper	70°	110°	110°	70°
Oriceps	90°	73°	107°	90°

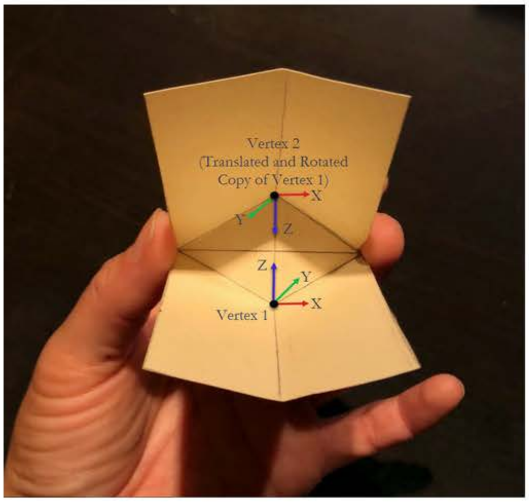

FIGURE 4. Location of the coordinate frames for placement of the model spherical linkage in the analysis of Shafer's chomper.

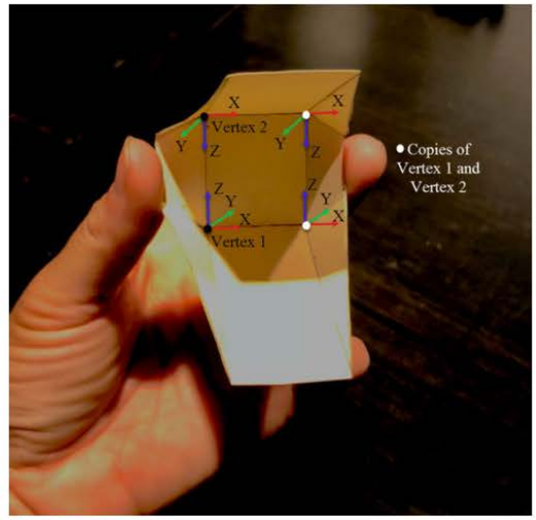

FIGURE 5. Location of the coordinate frames for placement of the model spherical linkage in the analysis of Oriceps.

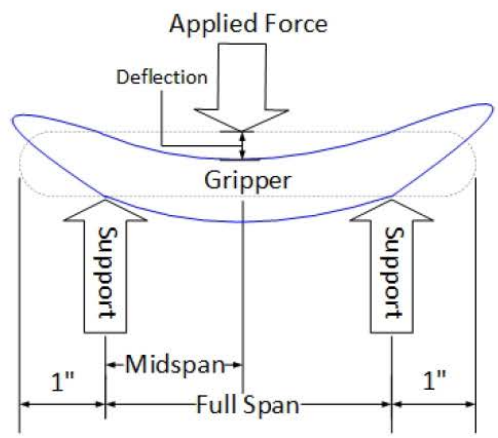

FIGURE 6. Three Point Bend Test Schematic.

Prototype Fabrication and Assessment

The prototypes for both the chomper and Oriceps inflatable grippers were manufactured from two sheets of heat sealable coated oxford fabric (Seattle Fabrics, Seattle, WA). An outline of the origami facets were traced onto the fabric. Vinyl cement (HH-66, RH Products, Acton, MA) was used to fuse the two layers and create facets or panels to make up the origami structure. Thick adhesive tape was used to reinforce the edges of each facet in the origami-based structure and also connect the facets together. Although various stiff materials and methods of reinforcing the facets were tested, thick adhesive tape was flexible and still allowed the structure to compact.

Tubing was inserted into each facet to allow for inflation by an air pump (Chamvis T-388 Electric Air Pump) . Cross-sectional geometry was reduced by adding a single stitch using upholstery thread at 2 inches along the center of largest facets. Valves were included to control air pressure to each tube in case of over-inflation, unintended deformation, or structural damage to each facet.

A three point bend test was used to assess the structure of the grippers. Since both grippers are symmetric, only the bottom half of each entire gripper was evaluated. The gripper was inflated in a flat, unfolded position. The bottom portion of the gripper to be tested was supported 1 inch from the distal edge of chomper mouth or Oricep bottom edge. Toward the center of the chomper mouth or Oricep gripper, a second support was secured 1 inch from the facet edge. Weight was applied to the inflated structure in the exact center of the two supports (see Figure 6). Load and deflection were tested three times then plotted and shown in the results section.

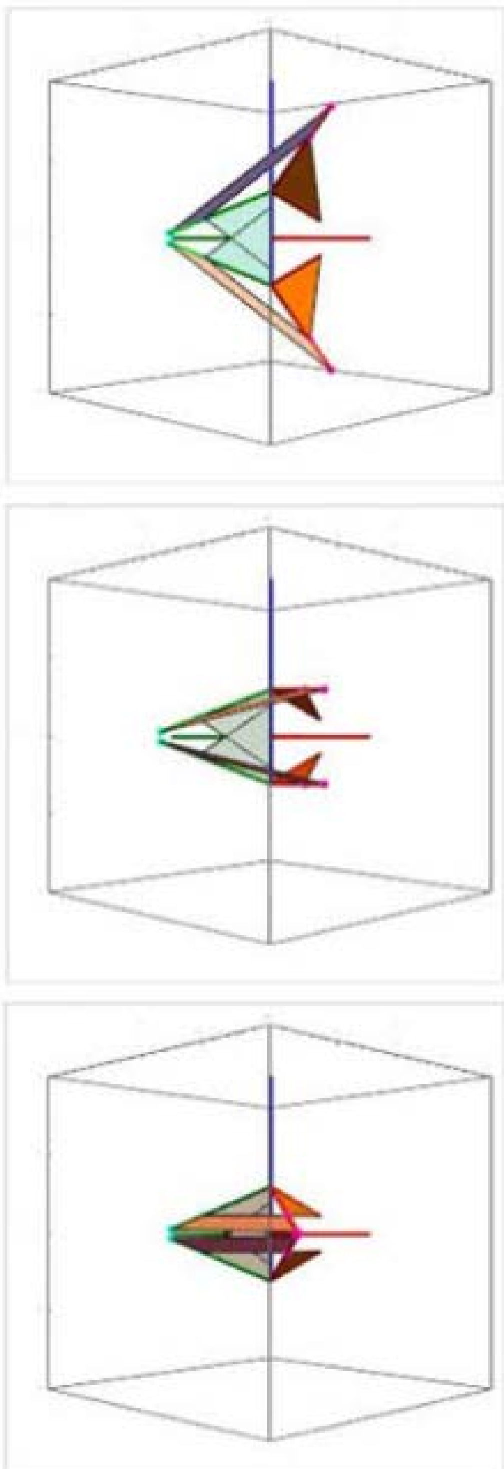

FIGURE 7. Computational modeling of Shafer's chomper with input angles increasing from 115 to 179 degrees from top to bottom.

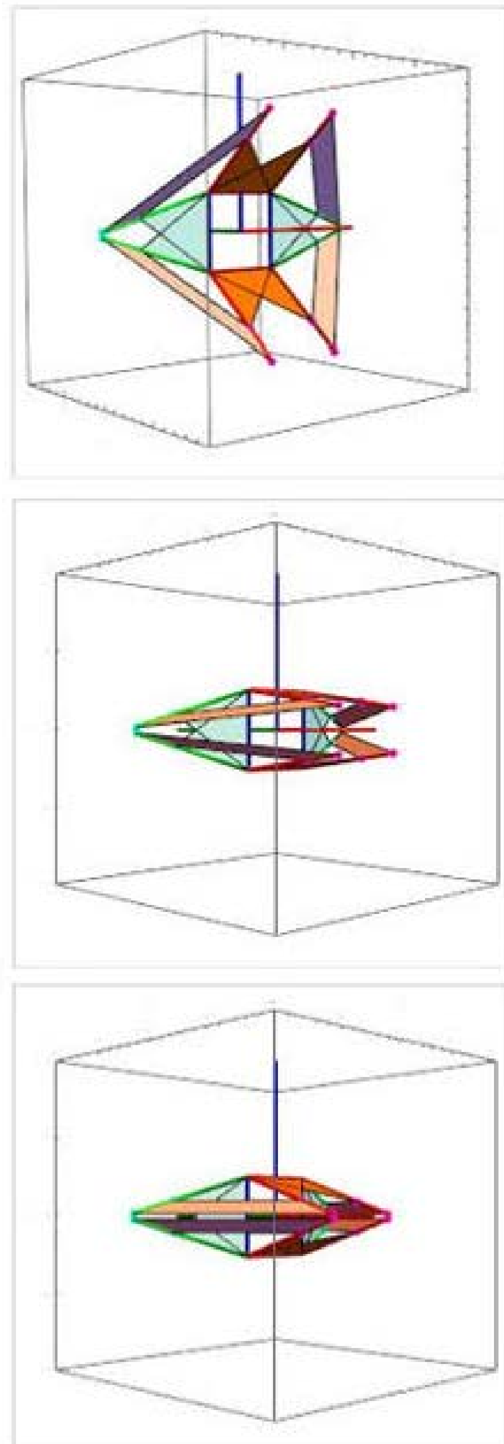

FIGURE 8. Computational modeling of Oriceps with input angles increasing from 155 to 175 degrees from top to bottom.

FIGURE 11. Shafer's chomper 3D configuration.

FIGURE 12. Oriceps 3D configuration.

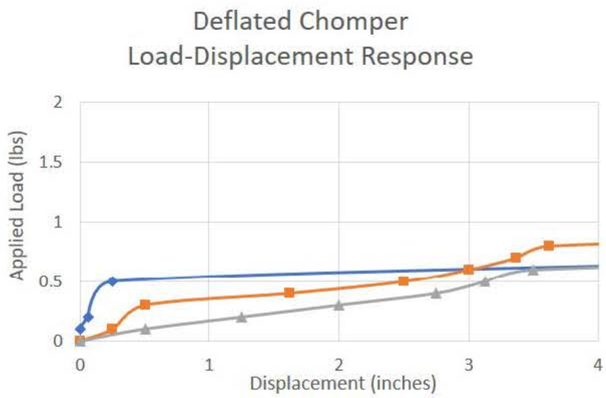

FIGURE 13. Structural assessment of deflated chomper.

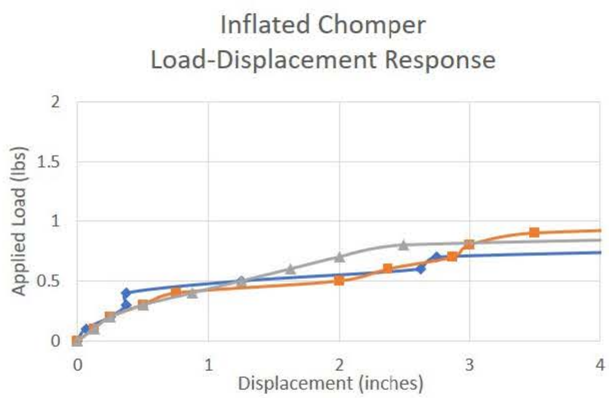

FIGURE 14. Structural assessment of inflated chomper.

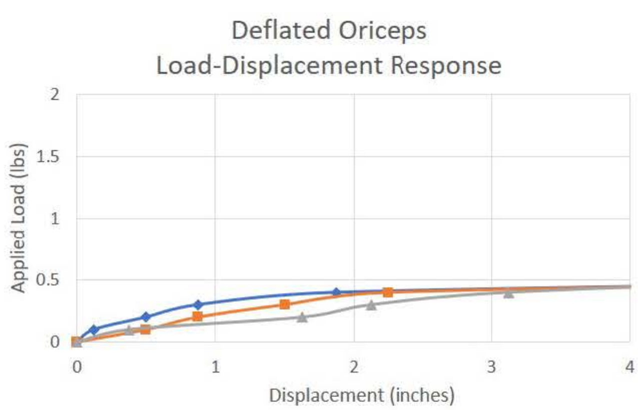

FIGURE 15. Structural assessment of deflated Oriceps.

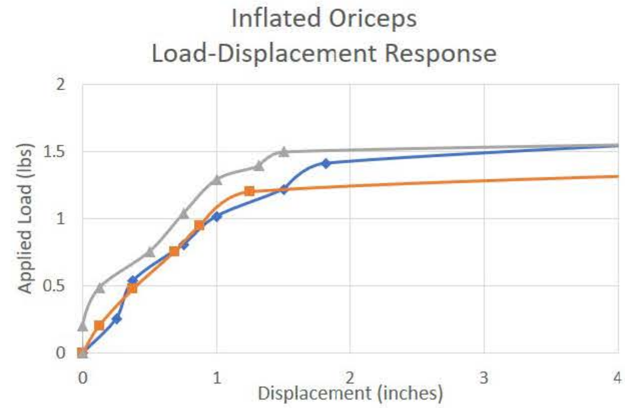

FIGURE 16. Structural assessment of inflated Oriceps.

to the deflated state. The Oriceps was able to support 212% more applied load in the inflated state than the deflated state. The geometry and design of the chomper panels led to more wrinkling in the inflated state. In a previous study, the impact of wrinkles was reflected in the nonlinear segments of the load-displacement curve and drastically increased deformation [13]. It is likely that this wrinkling in the chomper led to decreased ability to support heavier weight in the inflated state. More work will be done to minimize wrinkling of each gripper panel.

The authors plan to develop additional prototypes and further characterize gripper performance. In the next generation prototypes, fabric with greater thickness will be assessed to see if wrinkling can be minimized. The relationship between internal pressure and rigidity will also be characterized. Additional performance characterization can be applied as the model is scaled up or scaled down since the geometry and size of each inflated panel impacts inflation, and ultimately deformation under applied load. Two different methods of actuation will be applied: pulley blocks and pneumatic bag actuators modeled after existing inflatable actuation will be evaluated [22, 24].

5 CONCLUSIONS

Extensive research has been done on origami, action origami, deployable mechanisms, and simple inflatable vessels, but no study has evaluated gripper designs based on the combination of deployable, inflatable, action origami-inspired mechanisms. In this paper, a novel compact, lightweight, and easily manufactured gripper was fabricated, assessed, and motion was compared to a predictive model to report preliminary prototype results. Although more design refinement is required, this paper provides a preliminary assessment and further insight into design improvements for a deployable, inflatable, action origami-inspired gripper

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 1636017.

REFERENCES

[1] Shafer, J., 2010. *Origami Ooh La La!: Action Origami for Performance and Play*. CreateSpace Independent Publishing.

[2] O'Rourke, J., 2011. *How to Fold It*. Cambridge University Press.

[3] Guang, C., and Yang, Y., 2018. "Single-vertex multicrease rigid origami with nonzero thickness and its transformation into deployable mechanisms.". *Journal of Mechanisms and Robotics*, ***10***.

[4] Winder, B. G., Magleby, S. P., and Howell, L. L., 2009. "Kinematic representations of pop-up paper mechanisms". *Journal of Mechanisms and Robotics*.

[5] You, Z., and Pelligrino, S., 1997. "Cable-stiffened pantographic deployable structures—part 2: Mesh reflector". *AIAA Journal*, ***35***(8), pp. 1348–1355.

[6] Chu, Z., Deng, Z., Qi, X., and Li, B., 2014. "Modeling and analysis of a large deployable antenna structure". *Acta Astronautica*, ***95***, pp. 51–60.

[7] Qi, X., Huang, H., Li, B., and Deng, Z., 2016. "A large ring deployable mechanism for space satellite antenna". *Aerospace Science and Technology*, ***58***, pp. 498–510.

[8] Bowen, L. A., Grames, C. L., Magleby, S. P., Howell, L. L., and Lang, R. J., 2013. "A classification of action origami as systems of spherical mechanisms". *Journal of Mechanisms and Robotics*.

[9] Edmondson, B. J., Bowen, L. A., Grames, C. L., Magleby, S. P., and Howell, L. L., 2013. "Oriceps: Origami-inspired forceps". In ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, Vol. 1, American Society of Mechanical Engineers.

[10] Rhoads, B. P., and Su, H.-J., 2016. "The design and fabrication of a deformable origami wheel". In Volume 5B: 40th Mechanisms and Robotics Conference, ASME.

[11] Ishida, S., Nojima, T., and Hagiwara, I., 2013. "Application of conformal maps to origami-based structures: New method to design deployable circular membranes". In Volume 6B: 37th Mechanisms and Robotics Conference, ASME.

[12] Natori, M. C., Sakamoto, H., Katsumata, N., and Kishimoto, H. Y. N., 2015. "Conceptual model study using origami for membrane space structures - a perspective of origami-based engineering". *Mechanical Engineering Reviews*, ***2***(1), pp. 14–00368–14–00368.

[13] Ye, Y., Gan, J., Wu, W., Li, J., and Guo, G., 2018. "An experimental investigation of inflatable fabric beams of floating composite causeway". In Volume 11B: Honoring Symposium for Professor Carlos Guedes Soares on Marine Technology and Ocean Engineering, ASME.

[14] Zolock, J. D., and Tyrell, D. C., 2003. "Locomotive cab occupant protection". In Rail Transportation, ASME.

[15] Ustrzycki, T., Fernando, C., Ligori, M., and Papneja, N., 2009. "Inflatable truck roof deicing system". In Volume 13: New Developments in Simulation Methods and Software for Engineering Applications Safety Engineering, Risk Analysis and Reliability Methods Transportation Systems, ASME.

[16] Shahinpoor, M., and Asanuma, H., 2015. "Dynamic deployment of smart inflatable tsunami airbags (TABs) for tsunami disaster mitigation". In Volume 2: Integrated System Design and Implementation Structural Health Monitoring Bioinspired Smart Materials and Systems Energy Harvesting, ASME.

[17] Mortier, P., Beule, M. D., Loo, D. V., Impe, R. V., Verhegghe, B., and Verdonck, P., 2007. "Impact of the balloon folding pattern on the transient stent expansion behaviour: A finite element study". In ASME 2007 Summer Bioengineering Conference, ASME.

[18] Dong, J., Cheek, K., Duncan, J., and Kalnasy, A., 2017. "Design of portable patient lift system for assistant living homes". In Volume 5: Education and Globalization, ASME.

[19] Katsumata, N., Fujii, R., Natori, M. C., and Yamakawa, H., 2009. "Membrane modular structures with inflatable tubes and connective cables for future space applications". In Volume 2: Multifunctional Materials Enabling Technologies and Integrated System Design Structural Health Monitoring/NDE Bio-Inspired Smart Materials and Structures, ASME.

[20] Freeland, R., Bilyeu, G., Veal, G., Steiner, M., and Carson, D., 1997. "Large inflatable deployable antenna flight experiment results". *Acta Astronautica*, ***41***(4-10), aug, pp. 267–277.

[21] Kimura, H., Kajimura, F., Maruyama, D., Koseki, M., and Inou, N., 2006. "Flexible hermetically-sealed mobile robot for narrow spaces using hydrostatic skeleton driving mechanism". In 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE.

[22] Voisembert, S., Mechbal, N., Riwan, A., and Barraco, A., 2011. "A novel inflatable tendon driven manipulator with constant volume". In Volume 6: 35th Mechanisms and Robotics Conference, Parts A and B, ASME.

[23] Salomonski, N., Shoham, M., and Grossman, G., 1995. "Light robot arm based on inflatable structure". *CIRP Annals*, ***44***(1), pp. 87–90.

[24] Kim, H.-J., Kawamura, A., Nishioka, Y., and Kawamura, S., 2017. "Mechanical design and control of inflatable robotic arms for high positioning accuracy". *Advanced Robotics*, ***32***(2), nov, pp. 89–104.

[25] Ferreira, A. C. P., 2016. "Inflatable structures for robotic applications". Master's thesis, Instituto Superior Tecnico, Universidade de Lisboa, Mechanical Engineering.
[26] Liu, C., and Felton, S. M., 2017. "A self-folding robot arm for load-bearing operations". In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).
[27] Liu, C., Orlofsky, A., Kitcher, C. D., and Felton, S. M., 2019. "A self-folding pneumatic piston for mechanically robust origami robots". *IEEE Robotics and Automation Letters,* ***4***(2), apr, pp. 1372–1378.
[28] Niiyama, R., Sun, X., Sung, C., An, B., Rus, D., and Kim, S., 2015. "Pouch motors: Printable soft actuators integrated with computational design". *Soft Robotics,* ***2***(2), jun, pp. 59–70.
[29] Dettorre, J.-M., and Drago, F., 2018. Inflatable gripping device. World Intellectual Property Organization International Bureau, Apr. Patent WO2018 069064AI.
[30] McCarthy, J. M., and Soh, G. S., 2010. *Geometric Design of Linkages*. Springer Science & Business Media.