IEEE Control Systems Letters paper presented at
2023 American Control Conference (ACC)
San Diego, CA, USA. May 31 - June 2, 2023

Rapid Design and Production of Soft Actuators using Dynamic Modeling and Additive Manufacturing for Underwater Soft Actuators

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***Abstract*— Soft robotic actuators have repeatedly demonstrated their utility for underwater manipulation, particularly in the deep sea with delicate biological creatures and fragile artifacts. Up to this point, soft robotic actuators and gripping modules have been limited to relatively small prototypes that are on the same scale as a human hand. Scaling soft robotic grippers to larger sizes is a non-trivial task due to two major challenges: design and manufacturing. In this work, we present a complete and streamlined workflow of modeling, manufacturing, and testing scalable soft actuators that are directly produced using additive manufacturing methods and finite element modeling (FEA). The presented workflow is an iterative approach that uses information gathered from the FEA's simulation to further improve the simplified known initial model. To demonstrate this new workflow, a series of soft actuator designs were modeled, created and tested. Additionally, a more complex theoretical actuator design that has a non-uniform bending geometry is created and modeled. Once the actuator design matches what is desired, additive manufacturing is used to physically create it. Using this full process, an actuator design is easily scaled to almost three times its original length and is manufactured in under 36 hours. The scaled up actuators are arranged in a custom full gripping array to grasp a cylinder underwater in a predictive manner.**

I. INTRODUCTION

Recent advancement in soft robotics have led to a multitude of new designs, materials, and control approaches. Soft robots provide advantages that are often too challenging for traditional hard robots [1], [2]. Within the field of soft robotics, soft grippers have gained the most attention and applied research. Soft grippers outperform their traditional robotic gripper counterparts because they grasp a wide range of objects equally well, from delicate objects like eggs to heavier objects like a metal dumbbell with a singular design and/or control methodology [3]. Their flexible bodies allow them to fully wrap around a variety of objects regardless of their shape while not exerting dangerously excessive force [4]. There are a variety of soft gripper designs including pneumatic [5], hydraulic [6], [7], [8], Shape Deposition Manufacturing (SDM) [9], Dielectric Elastomer Actuator (DEA) [10], and Particle Jamming [11], but only a few have been demonstrated to operate in underwater applications.

Due to their capabilities of withstanding corrosive environments and high ambient pressures, while operating safely with delicate objects too difficult for normal grasping approaches, soft grippers are popular for underwater applications [12]. A variety of soft actuator designs have been tested and implemented with success in the underwater environment, the most common designs are hydraulically driven [13], [14] or are particle jamming [15]. Both designs have been used on remotely operated vehicles (ROVs) [16], [17] Hydraulically driven actuators have been shown to be effective with grasping corals and biological creatures thus improving the fidelity of biological sampling, [16]. An ultra-gentle hydraulic soft actuator was proven to be successful in grasping more delicate animals such as jellyfish [6]. Particle jamming has also shown great versatility in tightly grasping a variety of complex objects in less than ideal positions on the seafloor [11], [18]. Though several different actuator designs have demonstrated great success in the field, no manipulator can be a universal one.

Currently, underwater soft actuator designs presented in the literature are generally no larger than a human hand. Thus, it can be very challenging to grasp larger objects and to scale soft robotic systems for larger underwater platforms. Creating larger actuators, however, is challenging because soft actuators are complex, non-linear systems where altering any of its design parameters can potentially affect its control parameters, and ultimately how it behaves. Even with a good understanding of an actuator's behavior, due to the non-linear nature of their body, even the slightest changes in scale can have major implications in its performance [19]. Additionally, manufacturing a larger soft actuator is a non-trivial process. Traditionally, soft actuators have been created using a mold manufacturing process [16]. This process involves creating a mold for the whole actuator so that the flexible material can take the shape of the actuator in question. As a result, in order to manufacture and test a larger

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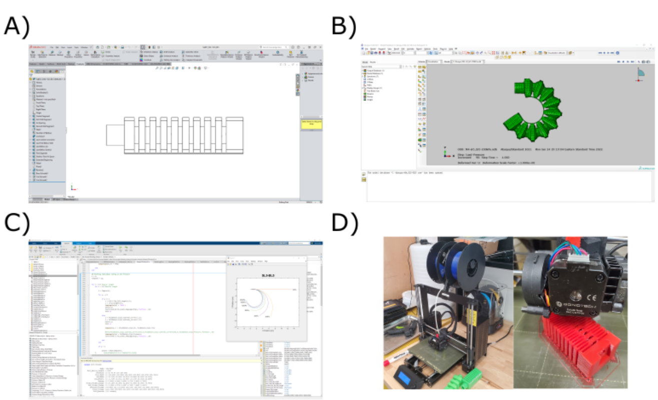

Fig. 1. Design and Manufacturing Process for Soft Actuator Design. A) Actuator designed in Solidworks, B) Same actuator being tested in Abaqus, C) Analyzing the information from Abaqus, D) Printing the Actuator Design with the Prusa

soft actuator a larger mold must first be created. This greatly increases the time needed to design, manufacture and test the new actuator especially for empirical iterative testing which is the most common approach for newer designs. Another approach to creating larger soft actuators is by combining several soft actuators together [20] or by combining soft actuators with harder components [21]. Though this is a more straightforward manufacturing process, it greatly complicates the control methodology.

The goal of this paper is to find an approach that overcomes the long iterative process that comes with prototyping soft actuators namely for larger actuator designs. This is done by leveraging additive manufacturing and dynamic modeling. Both processes have individually been shown to work effectively for designing soft robots. Rapid additive manufacturing is becoming a more popular approach for manufacturing as it removes the need to create molds for the soft actuator.

There are a variety of different rapid manufactured soft actuators that leverage different approaches and materials [22]. Some of the most common methods include injection molding [23], and 3D printing [24], [25], [26], [27]. However, this only shortens the iterative process rather than completely circumventing it. To completely avoid the iterative process, researchers have explored modeling as another approach. A variety of different dynamic programs have been used to model soft actuators [28], [29]. Some of the most popular programs are SOFA [30], [31], Ansys [32], [33], and Abaqus FEA. SOFA is an open source program that aims to give insight on how to control soft actuators [34] and simulate how they interact with objects [35]. On the other hand, Ansys [32], [33] and Abaqus FEA [25], [36], [37] are commercially available programs that use dynamic modeling to estimate the geometric shape of an actuator when in use. An issue with modeling is that it is not always an accurate portrayal of the physical world. Models are only as reliable as the information that they are given and how well the model program can handle nonlinear deformations.

In this paper, we describe a new design process that integrates additive manufacturing with dynamic FEA modeling for an underwater soft actuator. This process is shown in Figure 1. The aim here is to use both processes together to compensate for each of their shortcomings in order to gain further insight into the soft actuator's design, specifically control parameters and resulting geometric shape. This has been proven to work well with pneumatically controlled soft actuators [25], [29], [32]. Though custom FEA programs and custom advanced rapid manufacturing tools have been shown to be very successful, they are not easily accessible. Thus we employ commercially-available tools and methods that can be replicated. Using our design process, critical modeling information is gained about a new actuator design prior to production, a scalable version of the new soft actuator is manufactured and tested in a rapid fashion, and two complex hybrid actuator designs are created as a demonstration of the workflow's potential.

II. Materials and Methods

A. Workflow

Shown below is the major workflow steps proposed in this paper. The workflow outlines the whole process of designing, testing, analyzing, and manufacturing a soft actuator. This process is visually represented in Figure 1.

<u>Workflow List</u>

1) Design the actuator in Solidworks
2) Upload design into Abaqus FEA
3) Setup Abaqus FEA with proper material properties
4) Run Abaqus FEA simulations for internal pressure values and obtain data
    - Internal Nodal positions become .OBD file
    - External Nodal positions compile into .TXT file
5) Use AutoCAD to turn .OBD file into a physical part to get the actuator's internal volume
6) Use Matlab to calculate bend radius and bend angle values from .TXT file
7) Use Matlab to analyze all data to find correlations between values
8) Rerun Abaqus FEA with altered designs to find more correlations
9) Print out final actuator design with desired properties with Prusa

B. Actuator Design

For this project, a bellows-based soft actuator design is created. This design is inspired by a 3D printed actuator that was used in the ocean [17] and a 3D printed design from the Soft Robotics Toolkit [https://softroboticstoolkit.com] [38]. This design is meant to extend as much as possible by localizing a majority of the expansion to the face of the bellows. Combinations of varying thicknesses for a soft actuator design has proven to greatly affect how the system bends and deforms [19]. The core design employed is shown in Figure 2 and a list of the dimensions for that design are listed in Table II.

TABLE I
Variable Names and Values

Dimension Name	**Value**
Bellow Height	18.0 mm
Bellow Width	18.0 mm
Bellow Length	5.0 mm
Spacer Length	5.0 mm
Bellow Wall Thickness	1.2 mm
Bellow Face Thickness	2.0 mm
Strain Limiting Thickness	1.0 mm
Bellow Number	9.0

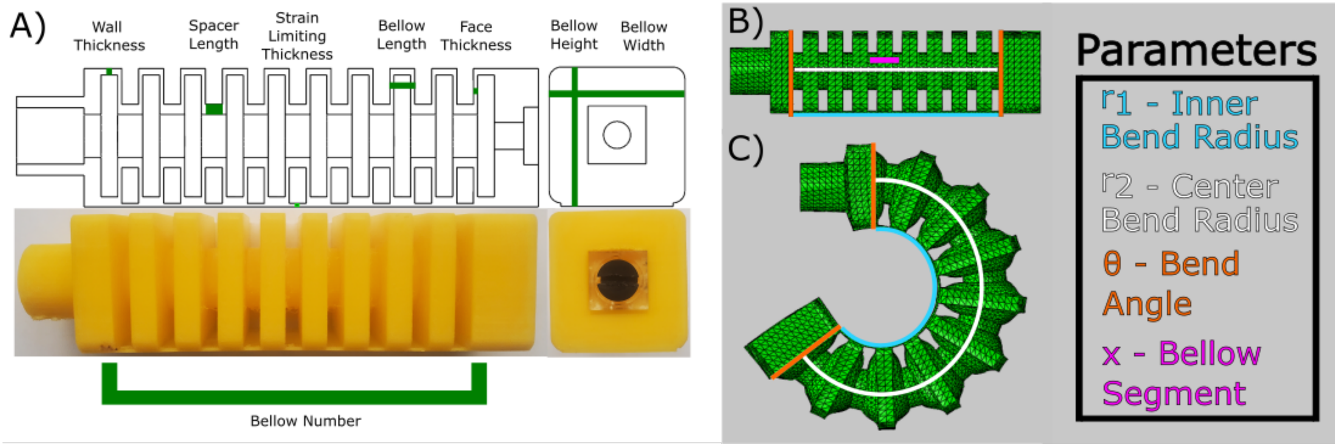

Fig. 2. Overview of the Actuator Design. A) Internal Geometry of the actuator with dimensions stated in Table II. The overall actuator design is a series of bellows integrated together. Through initial empirical testing, it was determined that a combination of having the "Bellow Face Thickness" be the thinnest dimension and having the "Bellow Wall Thickness" be at least twice as thick as the "Bellow Face Thickness" encourages the actuator to extend rather than expand out in multiple directions. The "Bellow Face Thickness" was chosen to be 1.2 mm thick because this is 3 times the width of the extruder head. According to a manufacturer's online article [https://flexionextruder.com/water-tight-prints/], three times the width of the extruder head is the required reliable thickness for a water tolerant print. The variable "Bellow Number" also includes the end bellows on the actuator even though those specific bellows have a slight variation in design. The actuator version shown in this paper has a strain limiting layer located at the bottom which causes the whole actuator to bend rather than extend linearly. B) Side view of the unpressurized actuator with r_1 (Inner Bend Radius) as the white line, r_2 (Center Bend Radius) as the light blue line, and purple is the length of the bellow. C) Side profile of the same actuator design at 200kPa where the angle between the two orange lines along the white line is the Bend Angle, θ.

Two key features of our actuator design is that it is easy to manufacture with a 3D printer and easy to use for testing and in the field.The actuator design is simplistic with straight flat walls and several right angles which is easy for a 3D printer to splice and print. Since a majority of 3D printers manufacture parts with a layered approach, flat walls with sharp angles are easier for a printer to print. To simplify with testing and field use, an end plug that utilizes a screw and a simple connector are implemented in the design. The end plug with a screw allows the whole actuator to be filled with water easily preventing any air bubbles from being trapped inside. The easy connector is a long cylindrical tube at the end of the actuator that is designed to fit over a custom barb hose fitting along with a worm gear hose clamp. This allows the actuator to be easily connected. Both the end plug and the custom barb hose fitting were printed with a Form2 (Form2, Formlabs, Somerville, MA, USA).

A simplified model of the soft actuator was created to gain insight on its performance based on the geometry. The model, which is shown in Equations 1-3, takes into account the geometry of an actuator that is composed of uniform bellows and observes how pressure affects its shape. This model shows the direct correlation between each bellow's extension and the full actuator's final bend radius and angle. To make things simple, two assumptions were made about the design. The first assumption is that each bellow design will act uniformly. The other assumption is that the final bend shape of the actuator is a uniform semi-circle shape. Using these assumptions, the final shape change can be estimated.

In the following equations, r_1 is the inner bend radius that lies on the strain limiting layer, r_2 is the bend radius along the center line of the actuator (center bend radius for short), θ is the bend angle angle between the first and last bellow on a given actuator, N is the number of bellows present in the actuator design, x is the length of the bellow, x_e is the extended length of the bellow that happens when the actuator is pressurized, h is the assumed constant distance between the two bend radii (r_1 and r_2). All lengths, r_1, r_2, x, x_e, and h, are in millimeters while θ is in degrees. All of the parameters are summed up in Table II.

TABLE II
PARAMETERS

Variable	Description	Units
r_1	Inner Bend Radius	cm
r_2	Center Bend Radius	cm
θ	Bend Angle	Degrees
x	Length of an individual Bellow	mm
x_e	Individual Bellow's Extension	mm
N	Number of Bellows	
h	Distance between r_1 and r_2	cm

$$2\pi r_1\left(\frac{\theta}{360}\right) = L_1 = Nx \quad (1)$$

$$2\pi r_2\left(\frac{\theta}{360}\right) = L_2 = N(x+x_e) \quad (2)$$

It is assumed that the two bend radius, r_1 and r_2 have the same center thus can be correlated by the distance between them.

$$r_2 = r_1 + h \quad (3)$$

Using these models, a correlation between the bend angle and the extension of each bellow is found which is shown in Equation 4.

$$\theta = x_e \left(\frac{180N}{\pi h} \right) \quad (4)$$

Furthermore, a correlation between the internal bend radius to the extension of each bellow is also found which is shown in Equation 5.

$$r_1 = \frac{hx}{x_e} \quad (5)$$

This model does not account for internal pressure or internal volume change and how it elongates each bellow. This is a nontrivial challenge due to the non-linear nature of the materials and the design of the bellow. The change of length is influenced by many factors including internal pressure and physical geometries such as wall thickness. This is where FEA modeling can help gain insight.

C. FEA Modeling

FEA simulation's reliability lies in the accuracy of the material's information and how well the software can handle complex non-linear motions. However, they can still be used as a simplified tool to gain some insights into the design [29], [39]. Thankfully, some elastic 3D-printing filaments, such as Ninjaflex®(Ninjatek, PA, USA) have well-defined material properties that can be successfully modeled using FEA [40]. Of all the FEA programs that support dynamic modeling, Abaqus FEA (Abaqus FEA, Dassault Systemes, Johnston, RI, USA) was chosen because there is recorded documentation that explains how to model and simulate soft actuators, including Ninjaflex. A guide for using Abaqus with soft actuators from the Soft Robotics Toolkit [https://softroboticstoolkit.com] [38] was used to setup the simulations. Data from Reppel et. al's paper [40] was used to setup Ninjaflex in Abaqus. Using Abaqus FEA an estimate of the actuator's geometric shape for a given internal pressure value can be obtained. Using the estimated geometric shape, the internal bend radius, bend angle, and internal volume can be collected.

D. Additive Manufacturing

Using additive manufacturing, specifically 3D printers, has its set of trade offs. The biggest benefit is that it greatly simplifies the manufacturing process by removing the need for molds. Typically a mold is required to shape softer materials into the soft robot. Molds are complex designs that have to ensure a correct alignment or else the soft actuator will be manufactured incorrectly. A problem with molds is that it has to be changed every time a new design needs to be manufactured. Thus, removing the mold will shorten the manufacturing process. However, 3D printing is limited in its material selection and has challenges printing with softer materials. The most common 3D printer is Fused Deposition Modeling, FDM, and the most common flexible material it can print with is Thermal polyurethane, TPU. In general, TPU is more stiff compared to what is normally used with mold manufacturing. A more stiff material reduces the effectiveness of a soft actuator as it is more restricted with its bending. Some custom printers can print with softer materials, but are often custom creations. However, since the goal of this process is to rapidly test different designs, the benefits of 3D printing the soft actuators greatly out weight the negatives.

For this paper, the aim is to have the actuator be printed with a FDM printer using a TPU material. Ninjaflex is one of the few TPUs that can be used by FDM printers and one of the more popular option. Unlike standard polymers that are used to manufacture soft actuators, such as Ecoflex®(Reynolds Advanced Materials, MA, USA), Ninjaflex is stiffer at 85A hardness. Ninjaflex has been proven to work well for several different 3D printed soft actuators [41]. The 3D printer used in this work was a Prusa i3 MKS3 (Prusa, Prague, Czech Republic) outfitted with a Bondtech LGX®extruder head (Bondtech, Värnamo, Sweden). Special attention was given throughout the printing process to ensure a low-humidity environment, which was found to have significant effects on the overall printing quality when using Ninjaflex TPU filaments.

III. Results

A. Actuator Matrix Result

To improve the simple model, a variety of actuator designs were tested through Abaqus FEA. The designs specifically varied in two dimensions, Bellow Length and Spacer Length. As it is in the model, increasing the lengths should only affect both bend radii. Running these altered designs through Abaqus will confirm this fact while exploring how other parameters, such as internal volume change, are affected. It is possible that altering the length of an individual bellow could affect its extension amount or change the amount of internal volume change for a given internal pressure. To explore how each parameter, both individually and collectively, affects the actuator's performance, a combination of lengths were tested. Both parameters varied in length from 1 to 5 mm at increments of 1 mm which yielded a total of 25 unique actuator configurations. Each design was tested from 0 to 200 kPa at set incremental pressure values. For consistency, the same number of bellows were used for all the configurations thus the overall lengths of each actuator varied.

As shown in Figure 3, there is a significant difference for the inner bend radius for the shortest and the longest variations (difference of about 1.5 cm), but they required about the same amount of volume change (difference of about 2.5 mL). Using the internal bend radius and the known distance from the center line of the actuator, an estimate of the length change for each bellow can be calculated. The total length change for all of the actuators were close in value (about 0.8 mm difference) for a given pressure indicating that

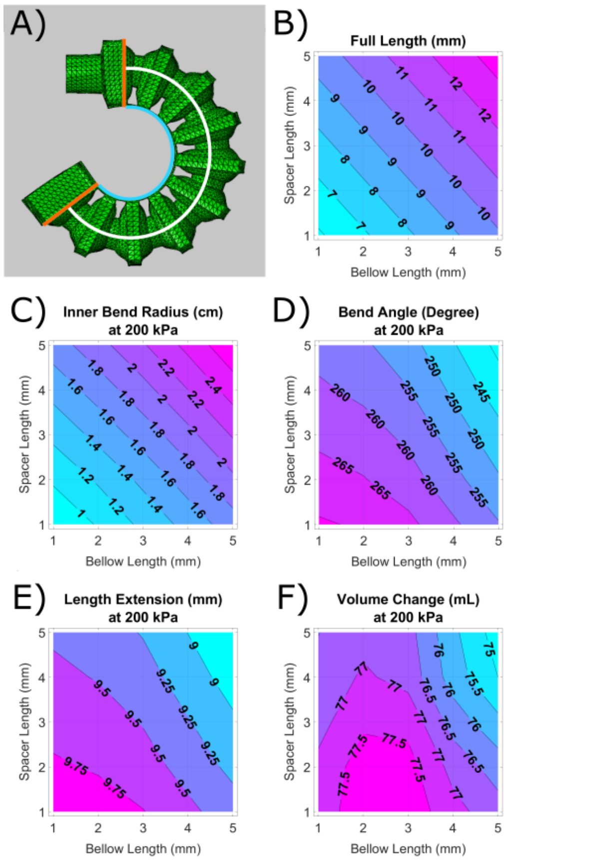

Fig. 3. A) Nodal position information saved from Abaqus FEA, the orange lines are the bellows used to calculate the Total Bend Angle which travels along the white line. The light blue line was used to calculate the Inner Bend Radius. B) Contour map of all the total lengths tested, C) Contour map of all the Inner Bend Radius at 200 kPa,D) Contour map of all the Bend Angle at 200 kPa, E) Contour map of all the Total Bellow Length Extensions at 200 kPa, F) Contour map of all the Volume Changes at 200 kPa

the two variables explored in this paper had a minimal effect on the system.

Since the internal volume change and bellow elongation values generally stayed around the same value, we can assume there is a consistent relationship regardless of the bellow's length. Figure 4A further demonstrates that there is a linear correlation between the two values. Using this information, Equation 4 reveals that the internal volume change also has a linear correlation with bend angle. This linear relationship can easily be added to the model. Taking the average extension and the average volume change, we have the new updated model that can estimate the elongation based on volume change for each bellow, v_b which is shown in 6. With this updated model, more precise and accurate control for this actuator can be achieved. This is a more reliable way to control the actuator since pressure has a nonlinear correlation to elongation which is shown in Figure 4B.

$$x_e = 0.123 v_b \tag{6}$$

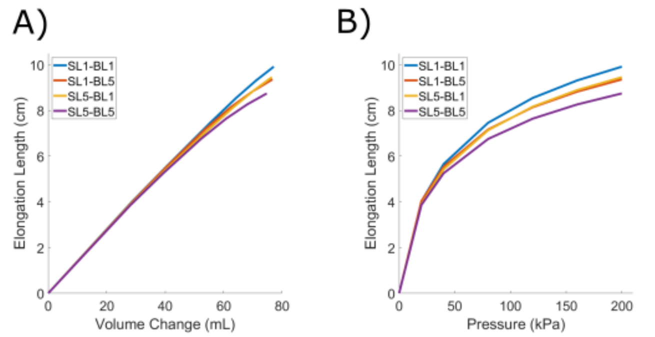

Fig. 4. Elongation comparison graphs. SL stands for Spacer Length and BL stands for Bellow Length and the numbers represent their length so /(SL1-BL1/) is Spacer Length and Bellow Length at 1 mm length. A) Pressure vs Elongation and B) Volume vs Elongation for a series of actuator designs. As shown here, Volume change is linear with respect to total elongation amount

B. Exploring Control Parameters

Using the Abaqus FEA data, further investigation was conducted to find the bellow arrangement that required the least amount of volume change to achieve the smallest bend radius. The shortest and the longest arrangements were compared for this exploration. For a fair comparison, more bellows were added to the shortest configuration so that it is close in length to the longest configuration. This will give a more accurate and fair estimation of how much internal volume change is needed. The Abaqus FEA results stated that the longest bellow configuration is 134.6 mm long and reaches an internal bend radius of 2.76 cm at 200 kPa or 74.76 mL internal volume change. Thus, the shortest configuration was elongated to have 26 bellows resulting in a total length of 133.4 mm. Using the internal bend radius value, the required internal pressure and internal volume change for the smallest bellow configuration can be calculated. For an internal bend radius of 2.76 cm, the elongated actuator will have an internal pressure of 14.28 kPa or internal volume change of 48.33 mL. This means that the smaller version is able to reach the same radius bend at 7.14% of the internal pressure and 64.65% of the internal volume change. This proves that the smaller version requires less internal pressure and less internal volume change for the same internal bend radius.

C. Scaled Actuators

Using this new approach, an elongated version of the actuator was designed and manufactured. The design of the elongated actuator slightly differed from the ones used in the 25 Abaqus trials and is shown in Figure 5A and 5B. This elongated version has a total of 24 bellows and has a total length of 225 mm long, 2.90 times the original length. The thickness of the actuator was slightly increased to ensure a proper print. The original version of the actuator takes about 13 hours to print while this elongated version takes about 36 hours. Using Abaqus FEA, it was discovered that a bend radius of 3 inches requires an internal pressure of about 45 kPa or volume change of 50 mL. To test this information, a three arm array was created to wrap around a cylinder

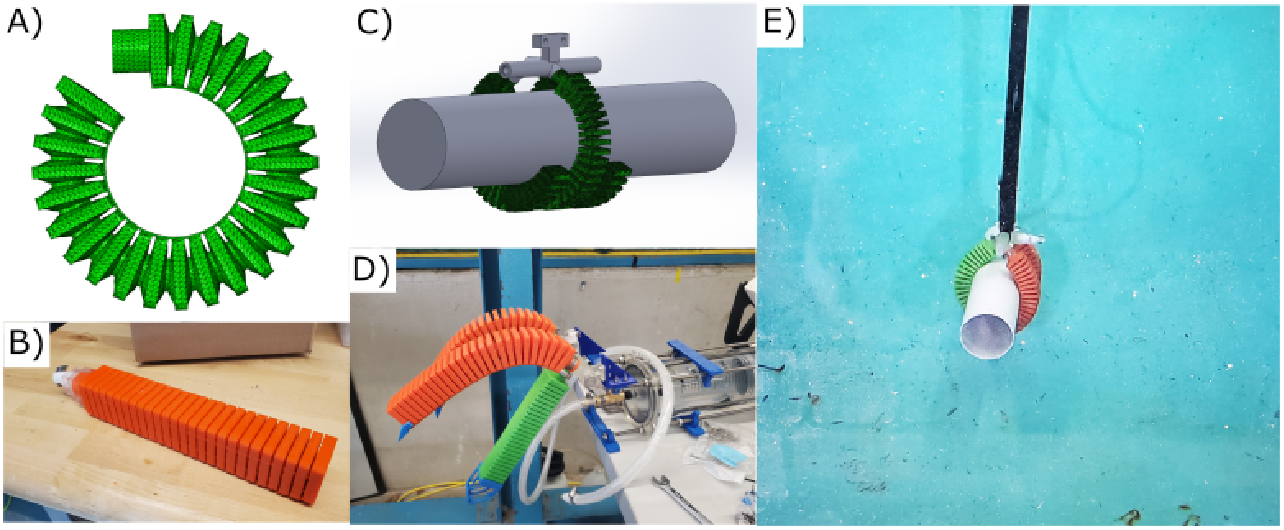

Fig. 5. A) Elongated Actuator's Abaqus test result at 45kPa, B) Physically printed Elongated Soft Actuator, C) Abaqus simulation of the Three arm array wrapping around a 6 inch diameter tube, D) Three arms array connected to a custom underwater pump, and E) Three arms array grabbing a 6 inch diameter cylinder at the bottom of the URI test tank

that has a 6 inch diameter. This array is shown in Figure 5D. With the calculated information, it was estimated that about 150 mL is required to have all three arms bend around the cylinder. To ensure a proper setup for the cylinder, the three arm arrangement was explored in Abaqus to find the best configuration which is shown in Figure 5C. Through the simulation, it was confirmed that the best arrangement has the arms at a negative 45 degree angle from the horizon. A central manifold, used to connect all three arms in the proper configuration, was 3D printed with a Form2. This configuration was tested in the accoustic tank located on the Narragansett Bay Campus at The University of Rhode Island shown in Figure 5E. For the physical test, a linear drive engine connected to a 200 cc syringe was used. The setup successfully picked up a 6 inch diameter cylinder at the bottom of the tank while the cylinder was laying at the bottom in different orientations.

D. Hybrid Actuator Design

Using the newly acquired information from the 25 Abaqus test, two complex actuators were designed and explored. These hybrid style soft actuators are composed of different bellow styles rather than just one. Though the current design proved to be effective in picking up objects underwater, it struggled if the array was not positioned correctly with respect to the target. If it was too far, then the arms would not properly come into contact with the object and if it was too close then it came into contact with the floor. Thus, hybrid systems with non uniform bending were explored. By using a non-uniform bending approach, the actuator can potentially ensure a better grasp on the object without worrying about interference from the floor. Two different proposed options are presented in Figure 6. Both utilize a combination of shorter and longer bellows to alter their final bending shape. The goal of these designs is to allow the actuators to first contact and gain a soft grip on the object which should help with alignment for the rest of the gripper.

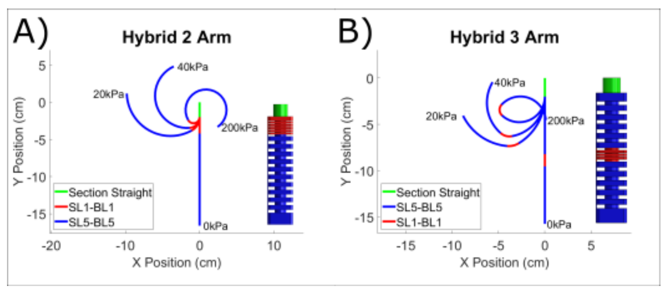

Fig. 6. Hybrid Actuator Designs, a) Two Arm Hybrid setup bending at various pressures and b) Three Arm Hybrid setup bending at various pressures

IV. Discussion

A. Scaling Results

Both adding more bellows and increasing the bellow's length by elongating the two dimensions explored in this paper had minimal affect on the bellow's performance which all matched initial expectations. All aspects did affect either the control requirements of the actuator or the actuator's performance. Adding more bellows caused the actuator to require more overall volume change while elongating the bellows altered the minimum bend radius that each actuator could achieve. Though this all matched initial assumptions, the direct correlation between the parameters and the soft actuators was still unclear. Simulations give a clear correlation and allows us to further improve our the model to have a better prediction. The next steps are to explore other parameters to see how they affect the actuator's control requirements and performance to gain an even more full understanding of this design.

B. Advantages of using 3D Printing with FEA Simulation

This new design approach significantly reduces the amount of time needed to design, manufacture, and test a new actuator design. If only one approach, 3D printing or FEA simulations, had been used, much less information about the actuator would be known without testing. If only 3D printing was used, conducting the 25 altered actuator test in a timely manner would be nearly impossible. The iterative approach would take a significant amount of time since multiple copies of each actuator would need to be printed and tested several tests all in an effort to get consistent data. Printing alone would take roughly 325 hour. However, with FEA modeling, a single actuator design needed about an hour and a half to test seven different pressures used for this analysis. Thus it took a cumulative 37.5 hours to test and record all the information for this test. On the other hand, FEA simulations can only provide theoretical information. For the 3 arm array, it was originally calculated that about 150 mL was required to wrap around the 6 in diameter cylinder. However, during the physical test, it was discovered that the full 200 mL was necessary to properly grasp it with a tight grip. This shows the limitation of FEA modeling.

C. 3D Printing Challenges

3D printing allows for more complex actuators to be manufactured rapidly; however, 3D printing flexible materials can be a challenging task. Not only are there a multitude of printer settings that each affect the print, but the material itself can be very sensitive and generally difficult to print with. In particular, TPU generally needs specific printer settings and need to be in a well controlled environment to print properly. Generally its best to have a slower feed rate with lower extruder tension to ensure a good print. TPU also needs to be in a well ventilated and temperature controlled room because it is sensitive to humidity. It can easily absorb water from the air thus negatively affecting prints. Even after fine-tuning everything and having it in a controlled environment, sometimes prints can be water tolerant but not pressure tolerant. When filled with water, there are no leaks, but when pressurized it begins to leak. A way to handle this is to further increase the wall thickness but even then sometimes the print quality is poor and leaks are still present. Thus, fine tuning a 3D printer to create good and reliable soft actuators can be a very difficult challenge.

D. Future Simulation Improvements

Though the simulation does well in estimating shape change, there are still aspects that it lacks. The most valuable addition to the workflow would be force estimation. While a custom printed actuator may successfully achieve the correct grasp geometry, this does not mean it is able to support the weight of the object. Further investigation is required to find a way to estimate force that an actuator exerts. General force estimation would be best as there are a variety of grasping approaches that a given actuator can exert. Understanding how the actuator's design and internal pressure or volume change affect the actuator's exerted force will greatly improve the design process. Currently, Abaqus FEA does not have a reliable way to measuring force exertion. Either a different simulation or another approach will need to be implemented to estimate the gripper's theoretical grasping strength.

V. CONCLUSIONS

In the presented work, we describe a workflow for simulating the behavior and rapid prototyping of bellows style soft actuators. The simulation is intended for use as part of the design process for directly printing manipulators to grasp specific objects. To demonstrate the method, a matrix of actuator geometries with varying design parameters was simulated with internal hydraulic pressures consistent with those used in current research in low pressure soft robotic underwater grippers. As a demonstration of the practical value of this approach, simulations were used to select an actuator design suitable for grasping a cylindrical target. The design was directly printed using flexible material, and successfully tested, underwater, on the cylindrical target.

The simulation approach makes it possible to methodically explore much larger design spaces and scale designs than would be possible through a purely hardware-based experimental approach. As an example, simulations were used to predict the behavior of 'hybrid' bellows design which vary the cross-sectional geometry of the bellows along the length of the gripper. Future work will further expand the range of design parameters and bellow's geometries in order to further tune the motion of the actuators, and expand the simulation effort to include prediction of grasp strength in addition to grasp shape.

ACKNOWLEDGMENT

The authors wish to thank Daniel Vogt and Kaitlin Becker for their support and advice related to 3D printing soft actuators. We thank the URI Department of Ocean Engineering for providing infrastructure and support for tank testing. This work was funded in part by NOAA's Office of Exploration and Research and the National Institute for Undersea Vehicle Technology.

REFERENCES

[1] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature*, vol. 521, pp. 467–475, 2015.

[2] S. I. Rich, R. J. Wood, and C. Majidi, "Untethered soft robotics," *Nature Electronics*, vol. 1, pp. 102–112, 2 2018. [Online]. Available: http://www.nature.com/articles/s41928-018-0024-1

[3] J. Hughes, U. Culha, F. Giardina, F. Guenther, A. Rosendo, and F. Iida, "Soft manipulators and grippers: A review," *Frontiers Robotics AI*, vol. 3, 11 2016.

[4] P. Polygerinos, K. C. Galloway, E. Savage, M. Herman, K. O'Donnell, and C. J. Walsh, "Soft robotic glove for hand rehabilitation and task specific training," *Proceedings - IEEE International Conference on Robotics and Automation*, vol. 2015-June, pp. 2913–2919, 6 2015.

[5] B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh, and G. M. Whitesides, "Pneumatic networks for soft robotics that actuate rapidly," *Advanced Functional Materials*, vol. 24, pp. 2163–2170, 4 2014. [Online]. Available: http://doi.wiley.com/10.1002/adfm.201303288

[6] N. R. Sinatra, C. B. Teeple, D. M. Vogt, K. K. Parker, D. F. Gruber, and R. J. Wood, "Ultragentle manipulation of delicate structures using a soft robotic gripper," *Science Robotics*, vol. 4, 8 2019.

[7] P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley, and R. F. Shepherd, "Soft robotics: Review of fluid-driven intrinsically soft devices; manufacturing, sensing, control, and applications in human-robot interaction," *Advanced Engineering Materials*, vol. 19, p. 1700016, 12 2017. [Online]. Available: http://doi.wiley.com/10.1002/adem.201700016

[8] G. Chen, X. Yang, X. Zhang, and H. Hu, "Water hydraulic soft actuators for underwater autonomous robotic systems," *Applied Ocean Research*, vol. 109, 4 2021.

[9] A. M. Dollar and R. D. Howe, "The highly adaptive sdm hand: Design and performance evaluation," vol. 29, 4 2010, pp. 585–597.

[10] S. Shian, K. Bertoldi, and D. R. Clarke, "Dielectric elastomer based "grippers" for soft robotics," *Advanced Materials*, vol. 27, pp. 6814–6819, 11 2015. [Online]. Available: http://doi.wiley.com/10.1002/adma.201503078

[11] S. Licht, E. Collins, G. Badlissi, and D. Rizzo, *A Partially Filled Jamming Gripper for Underwater Recovery of Objects Resting on Soft Surfaces*.

[12] R. A. S. I. Subad, L. B. Cross, and K. Park, "Soft robotic hands and tactile sensors for underwater robotics," *Applied Mechanics*, vol. 2, pp. 356–383, 6 2021.

[13] S. Kurumaya, B. T. Phillips, K. P. Becker, M. H. Rosen, D. F. Gruber, K. C. Galloway, K. Suzumori, and R. J. Wood, "A modular soft robotic wrist for underwater manipulation," *Soft Robotics*, vol. 5, pp. 399–409, 8 2018.

[14] B. T. Phillips, K. P. Becker, S. Kurumaya, K. C. Galloway, G. Whittredge, D. M. Vogt, C. B. Teeple, M. H. Rosen, V. A. Pieribone, D. F. Gruber, and R. J. Wood, "A dexterous, glove-based teleoperable low-power soft robotic arm for delicate deep-sea biological exploration," *Scientific Reports*, vol. 8, 12 2018.

[15] S. Licht, E. Collins, G. Badlissi, and D. Rizzo, *A Partially Filled Jamming Gripper for Underwater Recovery of Objects Resting on Soft Surfaces*, 2018.

[16] K. C. Galloway, K. P. Becker, B. Phillips, J. Kirby, S. Licht, D. Tchernov, R. J. Wood, and D. F. Gruber, "Soft robotic grippers for biological sampling on deep reefs," *Soft Robotics*, vol. 3, pp. 23–33, 2016. [Online]. Available: www.seaeye.com/falcon.html https://www.liebertpub.com/doi/10.1089/soro.2015.0019

[17] D. M. Vogt, K. P. Becker, B. T. Phillips, M. A. Graule, R. D. Rotjan, T. M. Shank, E. E. Cordes, R. J. Wood, and D. F. Gruber, "Shipboard design and fabrication of custom 3d-printed soft robotic manipulators for the investigation of delicate deep-sea organisms," *PLoS ONE*, vol. 13, 8 2018.

[18] C. E. Capalbo, D. Tomaino, F. Bruno, D. Rizzo, B. Phillips, and S. Licht, "A soft robotic gripper with neutrally buoyant jamming pads for gentle yet secure grasping of underwater objects," *IEEE Journal of Oceanic Engineering*, 2022.

[19] T. Ranzani, S. Russo, N. W. Bartlett, M. Wehner, and R. J. Wood, "Increasing the dimensionality of soft microstructures through injection-induced self-folding," *Advanced Materials*, p. 1802739, 8 2018. [Online]. Available: http://doi.wiley.com/10.1002/adma.201802739

[20] S. Li, S. A. Awale, K. E. Bacher, T. J. Buchner, C. Della Santina, R. J. Wood, and D. Rus, "Scaling up soft robotics: A meter-scale, modular, and reconfigurable soft robotic system," *Soft Robotics*, vol. 9, no. 2, pp. 324–336, 2022, pMID: 33769081. [Online]. Available: https://doi.org/10.1089/soro.2020.0123

[21] L. Rupert, T. Duggan, and M. D. Killpack, "Improved continuum joint configuration estimation using a linear combination of length measurements and optimization of sensor placement," *Frontiers in Robotics and AI*, vol. 8, p. 637301, 2021.

[22] R. L. Truby and J. A. Lewis, "Printing soft matter in three dimensions," *Nature*, vol. 540, pp. 371–378, 2016.

[23] M. A. Bell, K. P. Becker, and R. J. Wood, "Injection molding of soft robots," *Advanced Materials Technologies*, vol. 7, 1 2022.

[24] Y. L. Yap, S. L. Sing, and W. Y. Yeong, "A review of 3d printing processes and materials for soft robotics," *Rapid Prototyping Journal*, 2020.

[25] C. Tawk and G. Alici, "Finite element modeling in the design process of 3d printed pneumatic soft actuators and sensors," *Robotics*, vol. 9, 9 2020.

[26] D. Drotman, S. Jadhav, M. Karimi, P. Dezonia, and M. T. Tolley, "3d printed soft actuators for a legged robot capable of navigating unstructured terrain." Institute of Electrical and Electronics Engineers Inc., 7 2017, pp. 5532–5538.

[27] E. Sun, T. Wang, and S. Zhu, "An experimental study of bellows-type fluidic soft bending actuators under external water pressure," *Smart Materials and Structures*, vol. 29, 8 2020.

[28] M. S. Xavier, A. J. Fleming, and Y. K. Yong, "Finite element modeling of soft fluidic actuators: Overview and recent developments," *Advanced Intelligent Systems*, vol. 3, p. 2000187, 2 2021.

[29] G. Gu, D. Wang, L. Ge, and X. Zhu, "Analytical modeling and design of generalized pneu-net soft actuators with three-dimensional deformations," *Soft Robotics*, vol. 8, pp. 462–477, 8 2021.

[30] P. Ferrentino, A. Lopez-Diaz, S. Terryn, J. Legrand, J. Brancart, G. V. Assche, E. Vazquez, A. Vazquez, and B. Vanderborght, "Quasi-static fea model for a multi-material soft pneumatic actuator in sofa," *IEEE Robotics and Automation Letters*, vol. 7, pp. 7391–7398, 7 2022.

[31] X. Qi, H. Shi, T. Pinto, and X. Tan, "A novel pneumatic soft snake robot using traveling-wave locomotion in constrained environments," *IEEE Robotics and Automation Letters*, vol. 5, pp. 1610–1617, 4 2020.

[32] A. Zolfagharian, L. Durran, S. Gharaie, B. Rolfe, A. Kaynak, and M. Bodaghi, "4d printing soft robots guided by machine learning and finite element models," *Sensors and Actuators, A: Physical*, vol. 328, 9 2021.

[33] R. Wang, X. Zhang, B. Zhu, H. Zhang, B. Chen, and H. Wang, "Topology optimization of a cable-driven soft robotic gripper," *Structural and Multidisciplinary Optimization*, vol. 62, no. 5, pp. 2749–2763, 2020.

[34] A. G. Rodriguez, N. E. N. Rodriguez, and A. G. G. Rodriguez, "Design and validation of a novel actuator with adaptable compliance for application in human-like robotics," *Industrial Robot*, vol. 36, pp. 84–90, 2009.

[35] E. Coevoet, T. Morales-Bieze, F. Largilliere, Z. Zhang, M. Thieffry, M. Sanz-Lopez, B. Carrez, D. Marchal, O. Goury, J. Dequidt, and C. Duriez, "Software toolkit for modeling, simulation, and control of soft robots," *Advanced Robotics*, vol. 31, pp. 1208–1224, 11 2017.

[36] L. Gharavi, M. Zareinejad, and A. Ohadi, "Dynamic finite-element analysis of a soft bending actuator," *Mechatronics*, vol. 81, p. 102690, 2022.

[37] Z. Li, R. Huang, and Z. Liu, "A periodic deformation mechanism of a soft actuator for crawling and grasping," *Advanced Materials Technologies*, vol. 4, no. 12, p. 1900653, 2019.

[38] D. P. Holland, E. J. Park, P. Polygerinos, G. J. Bennett, and C. J. Walsh, "The soft robotics toolkit: Shared resources for research and design," *Soft Robotics*, vol. 1, pp. 224–230, 9 2014.

[39] G. Gu, D. Wang, L. Ge, and X. Zhu, "Analytical modeling and design of generalized pneu-net soft actuators with three-dimensional deformations," *Soft Robotics*, vol. 8, no. 4, pp. 462–477, 2021, pMID: 32822253. [Online]. Available: https://doi.org/10.1089/soro.2020.0039

[40] T. Reppel and K. Weinberg, "Experimental determination of elastic and rupture properties of printed ninjaflex," *Technische Mechanik*, vol. 38, pp. 104–112, 2018.

[41] X. Wang, H. Kang, H. Zhou, W. Au, and C. Chen, "Soft robotic finger with variable effective length enabled by an antagonistic constraint mechanism," *arXiv preprint arXiv:2112.13981*, 2021.