Buckling as Locomotion: Single Actuator In-Pipe Crawling Soft Robot Analysis and Friction Testing

24-673 Final Project Report

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Abstract: Over the last decade, the pipeline industry has increasingly embraced in-pipe robots for inspection, maintenance, and repair, leveraging their potential to reduce injuries, cut costs, and reach inaccessible areas. Despite the progress, soft robots haven't fully emerged as an industry standard. Recent studies have explored various designs and fabrication methods for soft robots in pipe applications, typically involving multiple actuators and complex controls. A novel single-pneumatic actuator approach has shown promise, achieving efficient movement through anisotropic contact with pipe walls. This movement largely depends on the frictional contact influenced by the leg's contact angle, surface area, and buckling geometry, which are determined by factors like notches, cross-sectional areas, and bending angles. We believe these leg design details are crucial, as they enable directional friction through a strategic buckling design, informed by previous strategies. Our research aims to investigate and characterize the aspects of angles and notches, as we believe these significantly impact the performance of soft pipe crawling robots. We will do this through physical experiments measuring friction force and theoretical modeling in Ansys. This investigation could guide the development of optimal buckling-driven actuation designs for future applications.

1 Introduction

Pipelines are vital to the infrastructure of modern society - essential for oil, gas, water, and sewage systems around the world. In the last decade, the pipeline industry has increasingly used in-pipe robots for the inspection, maintenance, and repair of pipelines. The advantage of using these robots is that they can minimize injuries, save money, and can non-destructively repair pipes where it would otherwise not be possible [2]. While rigid robots have had some success over the last decade for in-pipe travel, the hope here is that a clever in-pipe soft robot design can overcome this give-and-take relationship by creating a simple, highly maintainable, and flexible robot that has more pros than the current rigid designs. The intuition is that soft, bio-inspired in-pipe robots can move and conform to the changing shape of the pipe, advanced bends, and collect data in liquid environments - the main shortcoming of hard robots. Over the past five years, there have been a variety of papers published that documented different approaches to designing and fabricating soft robots for parallel pipe applications[3, 4]. However, there have been several challenges faced by soft robots in this application, including slow speeds, long actuation periods, long computational times, and a lack of smart locomotion to adapt to complex pipe shapes.

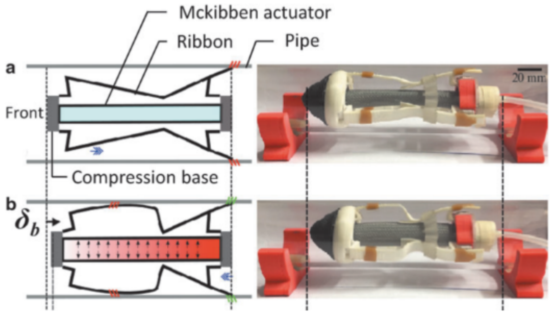

Figure 1: Lin et al. [1] focused primarily on actuation through bending and buckling of the back legs via a McKibben actuator. The legs were compressed against the inside wall of the pipe and held by high-friction anisotropic rubber. Elastic bands were used to control displacement in the trough region.

Our investigation in this paper was inspired by a design created by Lin et al,[1] whose design depended on anisotropy with notches and an angled back leg that buckled as an actuation mechanism. This design depended on two legs that were compressed against the inside of the pipe, with the friction propelling the device forward. The design also includes several high-friction rubber pads located on the ends of the legs, which contact the inside of the pipe and increase the friction. We wanted to go into more detail about the bending and controlled buckling of this leg design and how future designs can optimize these two factors to maximize feed-forward motion. Motion in soft robotics has often required advanced controls, multiple actuators, and modular design to improve degrees of freedom in movement. Mechanical instabilities such as snap-throughs, buckling, wrinkling, and creasing are being explored as a mechanism for soft robotic locomotion. By designing coupling-driven buckling movement to control friction responses, we can design soft robots that are able to move in a crawling motion whose control methods previously made them impractical[1, 7].

In single-pneumatic actuator designs1, as seen in Lin et al. [1], efficient forward motion is achievable through anisotropic contact with pipe walls. This anisotropy is largely influenced by the contact angle, buckling geometry of the legs, and surface area during contraction and expansion phases, which is the focus of our research. We aim to detail and test how the angle of the silicon rubber, cross-sectional area as a whole, and the notch introduction affect the performance of soft pipe crawling robot design through a series of physical experiments and theoretical modeling. The physical experiments will focus on measuring the frictional force of different angles of 3D-printed resin legs with rubber “feet” and understanding how the introduction of notches determines bending orientation. The theoretical Ansys experiments will focus on controlling the ratio of the geometric parameters of length, width, and height of the legs, as well as finding true buckling shape. We aim to use these both to identify optimal orientations and surface modifications for pipe contacts to enhance directional preference. This understanding extends benefits to broader soft robotic applications, reducing power consumption by minimizing backward slipping and loss of traction and extending use-case. Determining the most effective angles, materials, and roughing techniques could hopefully save energy costs, increase flexibility, extend use-case, and increase locomotion speed. The hope is these findings could be generalized to unlock new design combinations and applications in the field of in-pipe crawling soft robotics.

2 Methodology

2.1 Motivation Behind Examining Notches

Figure 2: A double-sided notch influencing the natural mode of buckling. [6].

Notches play a critical role in inducing and controlling buckling modes, essential for directional movement within confined spaces like pipes. This investigation focuses on how variations in notch placement, types, and quantity influence the robot’s locomotion efficiency. The objective is to determine if specific notch configurations can predictably direct the buckling process outwards such as seen in Figure 2. Predictable buckling could thereby enhance the robot’s navigational capabilities in different types of pipes with various orientations and obstructions. By studying the relationship between notch characteristics and buckling direction, we aim to accelerate the design process to get more reliable and controlled buckling locomotion.

Previous findings suggest that single-sided notches not only induce buckling but also contribute to the anisotropic properties that favor outward bending, as illustrated in Figure 1 [1, 6]. However, there is limited theoretical support that any generic single-sided notch would consistently direct the buckling mode. Our approach utilizes a double-sided notch, which has demonstrated effective control over buckling modes in prior experiments [6].

2.2 Predicting Leg Buckling Shape with Ansys

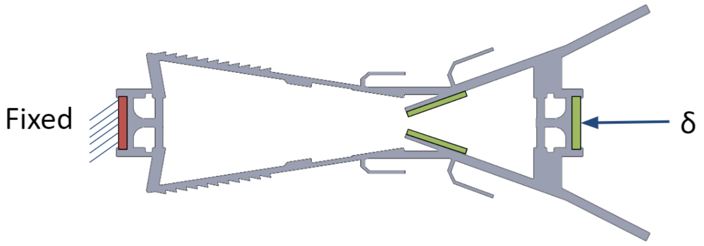

Figure 3: Analytical displacements and boundaries set up in Ansys.

To simulate the effect of compression from a McKibbon actuator on various leg designs, we tested twelve configurations with angles of 30, 40, and 54 degrees, featuring notches positioned at the left, middle, or right of the leg, as well as unchanged designs based on prior work by Lin et al [1].

In an ideal solution, compression is expected to cause outward buckling on the left side of the leg, facilitating contact with the pipe walls, while maintaining right-side contact. Referring to Figure 3, the simulation imposes specific boundary conditions: the left side is fixed, vertical displacement is restricted at the central trough (because it is linked to the actuator by a rubber band), and the right wall is limited to horizontal compressive movements.

A non-linear post-buckling analysis in Ansys helps predict the leg design's buckling behavior. This involves a sequence of Static Structural to Eigenvalue Analysis to Static Structural, using the first static solution as a basis for the Eigenvalue Buckling analysis, which then informs the final static analysis with pre-loaded scale factors of the mode shape and also the load factors of displacement to cause buckling.

This hierarchical structure ultimately allows us to get the realistic and appropriate deformation to cause buckling and leads to a realistic deformation structure as we are dealing with extremely large deformations with a soft material like plastic [8][9].

2.3 In-Pipe Squeezing with Ansys

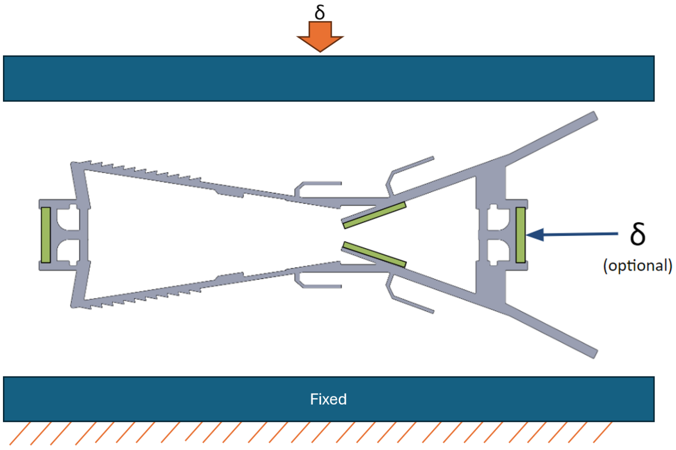

Figure 4: Analytical displacements and boundaries to set up the in-pipe squeezing Ansys analysis.

To evaluate the robot's operational performance within a pipe environment, we conduct simulations that model the interaction between the robot and two rigid pipe walls represented as beams. These beams, positioned symmetrically to the robot's leg, consist of a fixed bottom beam and a vertically adjustable top beam, simulating the robot squeezing into the tube.

Frictional contacts between the beams and the leg design are manually set up in Ansys to allow contact to occur during the robot's compression within the pipe. This setup allows us to observe the leg's deformation patterns under pressure, particularly focusing on any patterns in deformation (such as surface area and convex/concave bending), shear stress, or equivalent stress along the contact points to give insight to future designs for attainable net-forward movement designs.

In Ansys, we model two beams which represent rigid in-pipe walls the robot would squeeze into - seen in Figure 4. The beams are symmetric to the leg in each direction (including original vertical offset). The bottom beam is fixed whereas the top beam is vertically displaced to model the robot ”squeezing into” the tube. Large displacements are allowed, and the two separate manual frictional contact types are set up to allow contact between the beams and the leg design.

In addition, one analysis was done where the McKibbon compression movement described in Subsection 2.2 was modeled in a two-step static structural analysis to see if the buckling shape maintained its favorability when the legs are being squeezed. This analysis could be extended to be replicated for all designs to ensure the outward buckling direction is still favored in a variety of pipe diameters.

The base of the analysis relies on intuition and the quantitative and qualitative results we collected from our experimental setup. This analysis allows some insight to the ratio of forward-to-backward force and buckling success in multiple pipe diameters. The implications of which will be discussed in the results section.

2.4 Fabrication Method

To model the “legs” of the single-actuator pipe-crawling robot from Lin et al. [1], we printed the original structure used in the paper on a 3D printer in TechSpark with PLA. This created a deformable arm part with a CAD design that could be easily modified and changed to test different variables like angles and notches in the future. This first arm was modeled with a 27-degree angle, which produced an initial consistent measurement of 3.4 Newtons. However, we soon encountered an issue where the PLA began cracking under multiple bending tests. As a result of this, we worked with Micheal Vinciguerra to switch to using a Form 4 3D printer with Tough 1500 resin in the Rapid Prototyping Lab. Tough 1500 resin was chosen because it was both soft enough to bend and deform, with a tensile modulus of 218 ksi and a

51% strain at break (as per the manufacturer), but tough enough to stand up to repeated testing, with an ultimate tensile strength of 4786 psi. For this new set of testing legs, we also removed the middle bar to allow the leg to bend its full range of motion without extra supports.

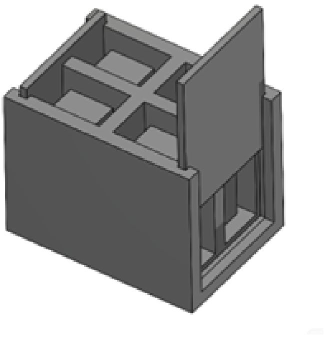

Figure 5: 3D-printed mold used to cast the rubber feet.

While this middle bar was in the original design, it was not a part of the leg itself. Places to attach hooks were also added to the top and bottom of the leg to better attach to the Preform software, which was used to position the print and generate supports before printing. The legs took roughly 10 hours to print and were post-processed using a double rinse of ethanol, cured with a UV light, and the supports were removed. We printed three of these legs at 54°, 40°, and 30°, as well as two at 30° with different notch locations.

The two silicone rubber elastomer feet were constructed using a generic smooth-on silicone elastomer, as recommended by Professor Majidi. This type of rubber product was chosen because it is soft enough to get good traction, but stiff enough that it won't tear or fret throughout the course of the experiment. Ideal trusted brands would be Dragon Skin or Vytaflex. However, due to budget constraints, we decided to order a generic version of this silicone rubber from Amazon, which was advertised as having a Shore hardness of 15A, a tensile strength of 4.2 MPa, and a viscosity of 6000-10,000 mPa/s.

To construct these feet, we combined parts A and B of the kit in a 1:1 ratio by weight and poured the solution into a 3D-printed PLA mold (Figure 5) before letting it cure overnight.

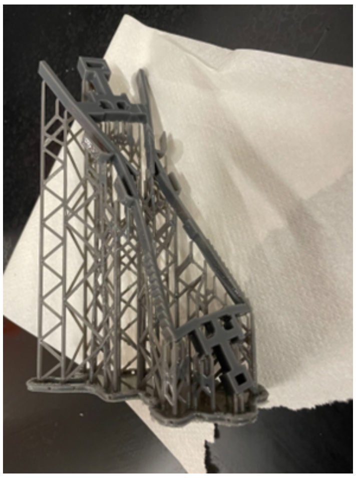

Figure 6: Each leg print was removed from the Form printer with extensive supports.

2.5 Experimental Setup

Our testing rig (Figure 7) was created with the purpose of testing the forward and backward frictional force needed to cause the outer "feet" of the leg to slip. To do this, we started by purchasing a horizontal hand crank platform from Amazon to ensure a smooth, level surface to mount our testing setup, and the hand crank mechanism provided an easily controllable and adjustable way to apply relatively consistent force. In addition to this, we also purchased a digital force gauge with a hook attachment and digital readout up to two decimal places from Amazon. We then used two screws to attach the force gauge to the test bed of the horizontal hand crank platform so that its location could be easily adjusted using the handle.

To model the inside of the pipe, we used two sheets of acrylic plastic mounted vertically onto plywood using angle brackets and screws. This ensures a smooth, rigid surface for the legs to pull and deform against it. The legs are then positioned horizontally, with each foot against each acrylic sheet, and pulled using the hand crank to measure the force. The hand crank was wound from the same starting point, and the data was video-recorded. The videos were processed with some approximations on time to compare across runs.

3 Results & Discussion

3.1 Experimental Results and Discussion

The data presented in Figure 8 shows the digital pull gauge's average force readings over time. These readings encompass all runs for all angle orientations. The results align with the intuition that the force decreases as the angle decreases; this is due to reduced pressure against the outside walls as the total width of the leg narrows, resulting in less outward push. Our Ansys simulations (Figure 12) support these observations, which demonstrate increased leg stress at higher angles, correlating directly with greater force exerted against the pipe walls. While these results are not surprising, they help validate our simulated model and serve as a sanity check.

Figure 7: Test bed setup and hand-crank, pictured with printed legs.

To achieve anisotropic motion, we are interested in the ratio between the forward and backward forces, shown in Figure 9. A greater than one ratio of backward-to-forward force is essential to achieve the motion described by Lin et al. [1]. This will ensure that the device slips forward instead of backward, therefore progressing through the pipe. We found through our experiments that this ratio favored smaller leg angles and, therefore, more evenly distributed stress along the foot. These stress concentrations are shown in Figure 13.

This experimental observation poses a contradiction to our expectations. Our team assumed a higher angle of attack would facilitate forward motion more effectively, a notion supported by Lin et al. [1], who say this behavior with stick-slip friction. Instead, the results demonstrate that smaller angles make forward slipping easier and backward movement more challenging.

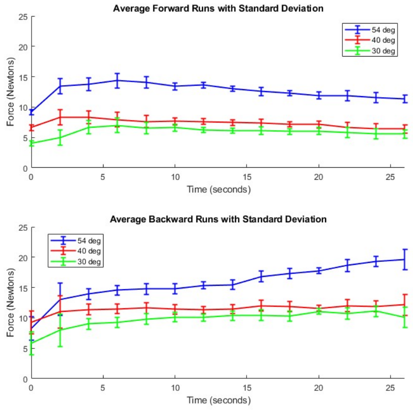

Figure 8: Force ratios across all runs.

This unexpected outcome suggests that the dynamics of force application and material interaction with the pipe walls at smaller angles are more complex than previously considered. To resolve this discrepancy and refine our understanding of the system's mechanics, further investigations are necessary. Future experiments should expand the range of angles tested and explore different pipe environments to more comprehensively characterize the anisotropic behavior observed. This will deepen our understanding of the fundamental principles governing the device's movement and guide the design for enhanced backward-forward forcing leg design.

3.2 Ansys Buckling Shape Results and Discussion

We initially validated our model using a simple double-notch beam. The predicted buckling direction aligned consistently between the Ansys simulations and physical experiments (refer to Figure 2). This validation provides confidence in our extended analyses on the leg design featuring similar double-notch configurations. Further, the Ansys eigenvalue buckling analysis of a simple non-directional notch supported our hypothesis that notches promote, but do not necessarily dictate, the direction of buckling. The analysis revealed over ten viable load factor modes, indicating potential for buckling in multiple directions.

Through our comprehensive study involving twelve different buckling analyses, several critical insights emerged. Notably, the introduction of a double-sided notch consistently resulted in a single, predominant mode of buckling. Although this mode did not always align with the preferred direction, it did enhance the predictability of the buckling behavior. Contrary to initial expectations, inducing outward buckling proved challenging. In the original configurations, buckling predominantly occurred inwards. Notably, only the designs with a 30-degree angle and a left-oriented notch demonstrated outward buckling when sub-

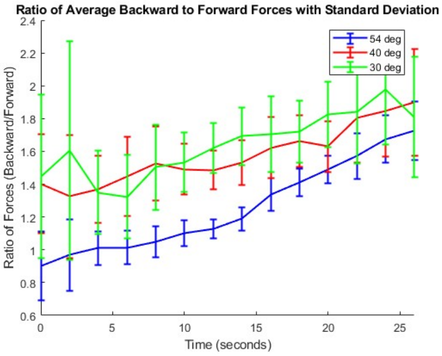

Figure 9: Average force for backward and forward runs across all angle orientations.

jected to extreme deformation. A demonstration of the inward buckling and ultimate success of the altered design can be seen in this video.

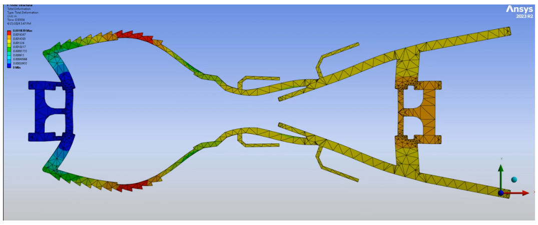

Figure 10: Ansys post-buckling results for the altered 30 degree with left notch-orientation design.

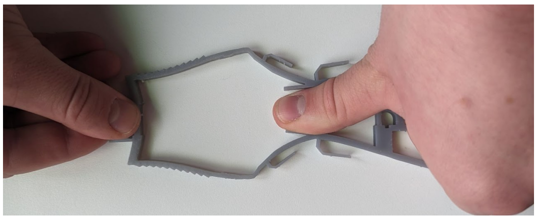

Figure 11: Physical prototype bending. Keeping the middle somewhat locked such as the analysis.

This unexpected behavior prompted a redesign focused on enabling outward buckling on the 30-degree angle with left-oriented notch leg design. Video animations of the compression tests highlighted that the ribbed design of the leg contributed to its structural integrity, and with it angled inward it thereby favoring inward buckling. To counteract this, we introduced a standard notch in the redesign to weaken the robust section, thus promoting outward buckling. This iterative design process ultimately yielded a model that reliably buckled outwards. A physical prototype was subsequently produced and successfully validated against the Ansys results, as shown between Figures 12 and 13.

This study underscores the significance of strategic notch placement in the design of buckling-induced locomotion mechanisms. Our findings demonstrate that employing double-sided notches can effectively encourage consistent and predictable buckling directions, essential for the precise control needed in soft robotics applications. Furthermore, the introduction of notches to promote buckling has been crucial in achieving desired movement patterns, specifically in facilitating outward buckling. These insights provide a valuable framework for researchers and engineers aiming to optimize buckling behaviors in soft robotic systems. By implementing these design principles, future developments can leverage controlled buckling to enhance the functionality and efficiency of locomotive mechanisms in various applications.

3.3 Ansys In-Pipe Squeezing Results and Discussion

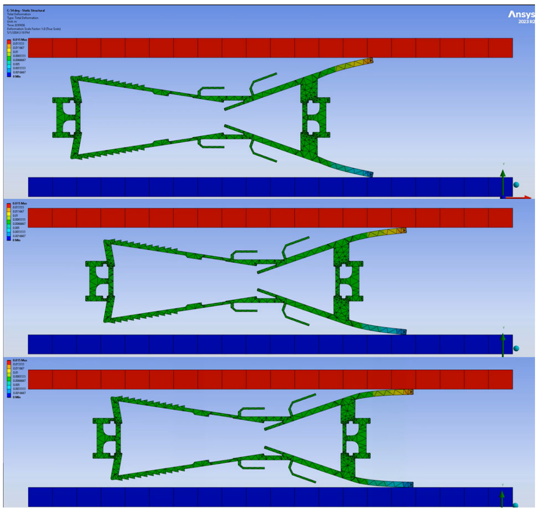

Figure 12: Ansys in-pipe squeezing total deformation results for 54, 40, and 30 degree configurations from top to bottom.

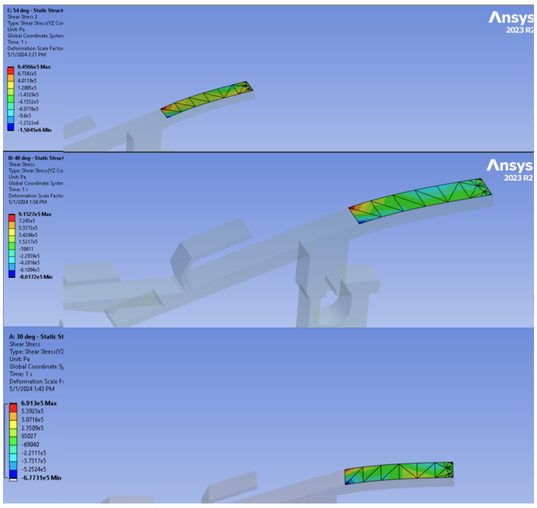

Figure 13: Ansys in-pipe shear stress along the top face of the leg face in contact with the wall when squeezed. 50, 40, and 30 degree configurations from top to bottom.

Our Ansys simulations provide critical insights into the operational performance of the robotic leg within confined pipe environments. By modeling the interaction between the robot's leg and two rigid pipe walls, represented as beams, we assessed the deformation patterns and shear stress distribution under varying conditions of pressure and compression. The three leg designs modeled were the same ones that were printed and tested experimentally.

The simulation setup involved a fixed bottom beam and a vertically adjustable top beam to replicate the squeezing action of the robot's legs into the pipe. This arrangement allowed for detailed observation of the leg's deformation under compression and the associated shear stress along the contact points. We specifically monitored the areas showing maximum shear stress, which were consistently located at the last part of the leg in contact with the wall. Notably, our data showed a significant increase in shear stress from 30 and 40 to 54 degrees, with stresses nearly doubling, mirroring the trends observed in our force collection data.

Combining the empirical data collected from experiments and simulation results, while a larger overall force can be simulated, there is not quite a clear connection in force ratios between forward and backward movements across the tested angles and the patterns in deformation and shear stress. This discrepancy is crucial as it indicates the efficiency of the leg's design in achieving forward propulsion. However, we can say that the observed increaesed contact area and deformation patterns along with a reasonably close stress concentration in the lower angles fascilitate more effective propulsion.

In addition, a two-step pipe squeezing and compression Ansys simulation was performed which proved that the altered design was able to buckle outwards and make contact with the wall even when the leg structure changed from the outward legs being squeezed. The results of total deformation and buckling structure can be seen in Figure 14.

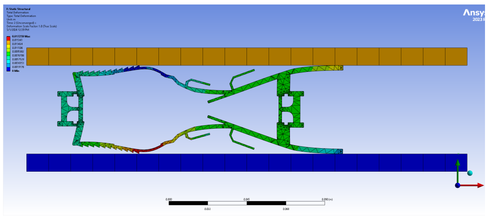

Figure 14: Ansys in-pipe squeezing and buckling total deformation results.

This second analysis could be extremely important to researchers to check their designs still will buckle outwards in different pipe diameters, pipe roughness techniques, and for any altered leg designs. In addition, this analysis would allow researchers to determine where to optimally place rubber caps, and even design them optimally to increase contact area where desired. This is because the contact points are clearly shown.

Combining these three analyses allows increased understanding to the success of buckling as locomotion, anisotropic success, and helps expedite the iterative design process - especially since printing flexible plastics can take a half day on modern printers.

4 Conclusion

In conclusion, the development of in-pipe robots has become increasingly relevant for inspection, maintenance, and repair applications, driven by the need to access hard-to-reach areas and reduce operational costs. Soft robotics has emerged as a promising solution in this domain, with various designs exploring the use of multiple and single actuators, complex controls, and novel structural elements to enhance functionality and efficiency.

Our research primarily focused on characterizing the actuation mechanisms of Lin et al. [1] leg design, with some adjustment, through experimental and simulation studies. We investigated the impact of leg angles and notches on the bending and buckling behaviors of 3D-printed legs with silicone pads, complemented by Ansys simulations that varied leg dimensions. These studies aimed to identify orientations that maximize anisotropic actuation potenial.

Our findings indicate that leg angle significantly affects the force dynamics during robot movement. Specifically, smaller angles favored a higher backward-to-forward force ratio, enhancing forward motion efficiency by reducing the force required for forward slips compared to backward movement. This characteristic is critical for allowing locomotion in soft pipe crawlers with a single pneumatic actuator.

The inclusion of notches in the legs was found to facilitate buckling at lower forces and dictate the buckling direction, aligning our physical test results closely with our Ansys simulations. These insights could inform the design of other bio-inspired soft robotic systems, broadening their applications in pipe inspection and other areas requiring adaptable and efficient movement.

Ultimately, by refining the angles, materials, and structural configurations of soft robotic legs, we aim to develop designs that save energy, enhance flexibility, and expand the capabilities of in-pipe robots. This research supports the ongoing evolution of soft robotics and opens up new possibilities for their application across various industries.

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