Design Optimization of Soft Pneumatic Bending Actuator

REPORT

PROBLEM STATEMENT

MOTIVATION

The emergence of Industry 4.0 has spurred a crucial objective: creating machines capable of safe and seamless interaction with humans while navigating diverse and unpredictable environments. Despite the widespread reliance on robotics to accomplish these tasks, a fundamental hurdle persists: traditional robots need help operating safely and effectively in uncertain settings or when handling fragile objects. This limitation significantly curtails their potential applications across industries.

Efforts are underway to tackle this challenge, recognising its alignment with Sustainable Development Goal 9 (SDG 9)[1], emphasising the advancement of industry, innovation, and technology transformation while promoting sustainable practices. The goal is not just to innovate in robotics but to do so in a manner that fosters environmentally friendly and sustainable development.

The India G20 initiatives place particular emphasis on addressing these pressing issues. By prioritising the development of technology capable of navigating uncertain terrains and interacting safely with humans, these initiatives strive to pave the way for a future where innovation drives progress while ensuring that these advancements align with sustainability goals.

SURVEY

Soft Robotics could be an ideal solution to this problem due to their compliant and flexible structures, allowing for safer interactions, adaptability to diverse environments, and improved agility when handling fragile objects or interacting closely with humans. Soft robotics have been an emerging field with soft actuators and grippers that have been increasingly used in industries worldwide, and their usage will increase. According to the **2023 Robotics Manufacturing Status Report**, soft actuators and grippers expect a **compound annual growth rate of 35.1 per cent between 2022 and 2027**[2], with biomedicine, food, and agriculture set to benefit. Almost **one-third (32 per cent) of robotics industry experts**[2] believe that soft robotics and new materials will impact how robotics manufacturing will develop in the next five years.

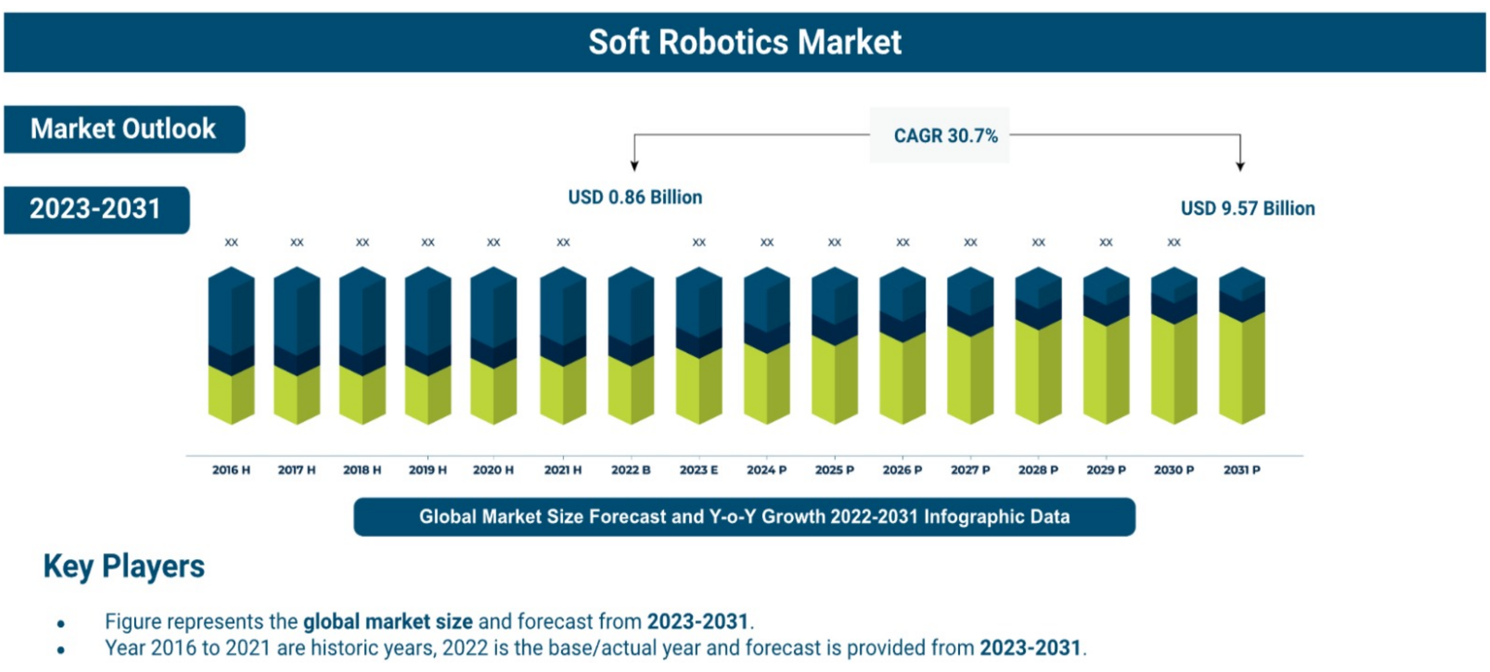

Fig 1: Soft robotics rise in the market in upcoming years (Source: Growth Market Report Analysis)

PROPOSED SOLUTION

INSIGHTS

With the emerging importance of soft robotics, quite a lot of work has been done on optimising soft robotic designs, like taking inspiration from nature and validating them through modelling techniques to get sustainable and efficient designs. In this project, we aimed to optimise the design parameters of a soft pneumatic actuator using finite element methods. **We aimed** to achieve maximum bending at specific pressures while minimising stress concentrations. Additionally, we explored alternative designs to enhance efficiency within soft robotics. This project relates to our problem statement in the following ways: -

1.) **SDG 9: Industry and Innovation:** With proper optimisation, soft robots can be highly efficient, making them capable of having a similar impact on Industry 4.0 as traditional robots have in Industry 3.0.

2.) **Technological Transformation:** We have focused on the FEM approach for the testing of Soft Pneumatic Actuators optimisation, which highlights the role of advanced simulations in shaping the future of engineering by enabling more precise, efficient, and sustainable designs. Thus, both soft robotics applications and optimisation can contribute to transformation in technology.

3.) **Green Development:** The choice of silicon for our actuators aligns with biocompatibility standards, and we have used manufacturing techniques like 3D printing to curb material waste compared to conventional methods. This conscious selection of materials and processes fosters sustainable development.

The Finite Element Method (FEM) stands out as our chosen approach for the testing of Soft Robotics optimisation due to its adaptability in handling complexities without intricate analytical models. FEM accommodates deformations and material complexities within Soft Pneumatic Actuators, aiding in predicting performance and identifying weak areas. We also try to optimise FEM for computational efficiency while maintaining accuracy and have utilised Ansys for this purpose[3].

TESTING

The following steps have been followed in testing the Soft Pneumatic Actuator in Ansys:-

1.1 Material assignment: We chose the **Yeoh 3rd order**[4] model and its parameters for **Silicon** for the material assignment. The Yeoh model is chosen because it only needs a small amount of experimental data to get reasonable numerical results. It can also describe a wide range of deformation. The reason for choosing Silicon material is the abundance of its experimental material data, and it is biocompatible and flexible.

Properties of Outline Row 3: Elastomer Sample (Yeoh)

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	2330	kg m^-3
4	Uniaxial Test Data	Tabular	
5	Scale	1	
6	Offset	0	Pa
7	Biaxial Test Data	Tabular	
11	Shear Test Data	Tabular	
15	Yeoh 3rd Order		
16	Material Constant C10	0.06	MPa
17	Material Constant C20	0.005	MPa
18	Material Constant C30	0	MPa
19	Incompressibility Parameter D1	0.01	MPa^-1
20	Incompressibility Parameter D2	0.01	MPa^-1
21	Incompressibility Parameter D3	0.01	MPa^-1

Fig 2: Material properties and parameters[4][5]

1.2 Meshing parameters: I tried different mesh methods along with various element sizes to observe the trend of the number of elements and element quality. A global element size of 1 to 2 mm is ideal for modelling using the Multizone or Hex Dominant methods for body sizing. The Multizone method and Hex Dominant mesh give good results regarding computation efficiency and element quality. I also tried using the Cartesian method but found it computationally heavy. The multizone method gave better element quality than Hex Dominant mesh while being more computationally efficient. I have used symmetry to reduce the number of nodes.

1.3 Loads and boundary conditions: The load applied is of internal pressure of 1 KPa in tabular form. This pressure is applied slowly with 0.1 KPa in each time step. Other than this, standard earth gravity has been applied while one end is fixed as a boundary condition. For better convergence of results, I have used neqit,50[3], which increased the number of iterations per substep.

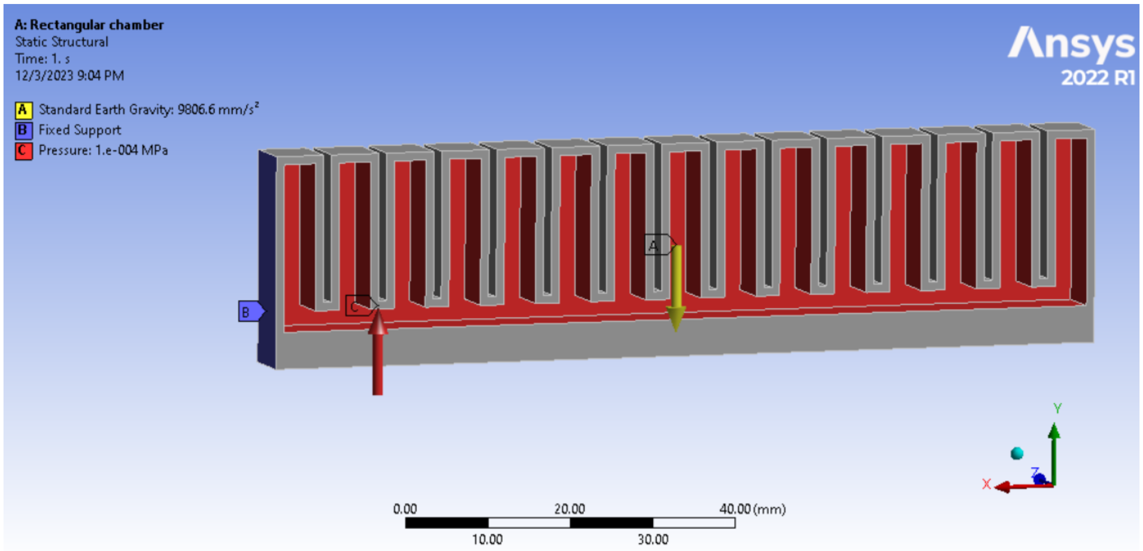

Fig 3: Load

1.4 Design Optimization of Soft Pneumatic Actuator: There are quite a few parameters, like wall thickness, the height of chambers, the width of the chamber, and the bottom layer thickness, which can be altered and have an effect on stress-strain and deformation of the Soft Pneumatic Actuator.

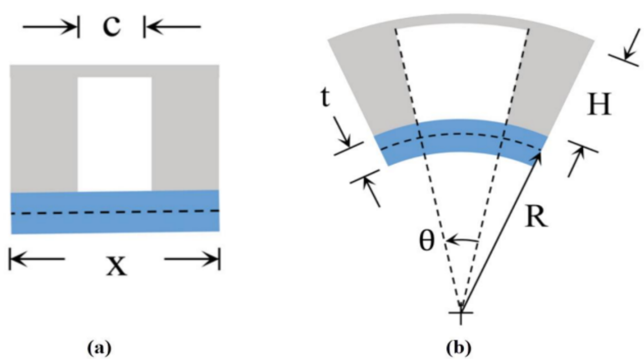

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Fig 4: The design parameters of the Soft Pneumatic Actuator[6]

There have been theoretical derivations to get the relation between the parameters mentioned in the above figure and the curvature of the Soft Pneumatic Actuator. One such equation is mentioned

$$\kappa = -\frac{6(1-\gamma^2)PH^2c}{Et^3x}$$

Here **K** = curvature of Soft Pneumatic Actuator[6].

Based on this equation, I observed two relations and tried validating them through Ansys simulations.

1.) Curvature is inversely proportional to the thickness t of the bottom restraining layer.

2.) Curvature is directly proportional to the height H of the chamber.

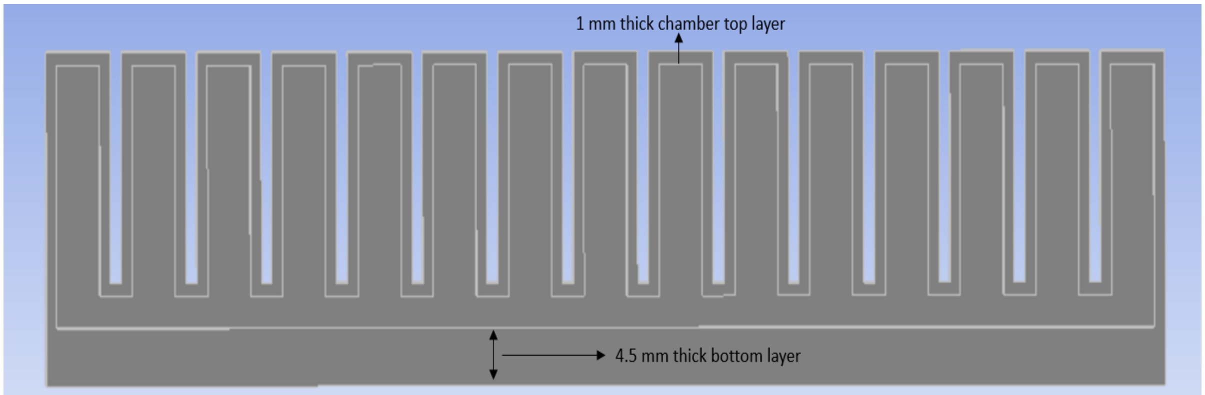


Fig 5: Initial CAD model of Soft Pneumatic Actuator

Based on these observations, we made changes in the design of the initial CAD model, like decreasing the bottom layer thickness to 1 mm and increasing the chamber height by 1 mm. I have kept the thickness of the chamber walls at 1 mm. Minimal thickness of chambers also helps in large bending of the actuator.

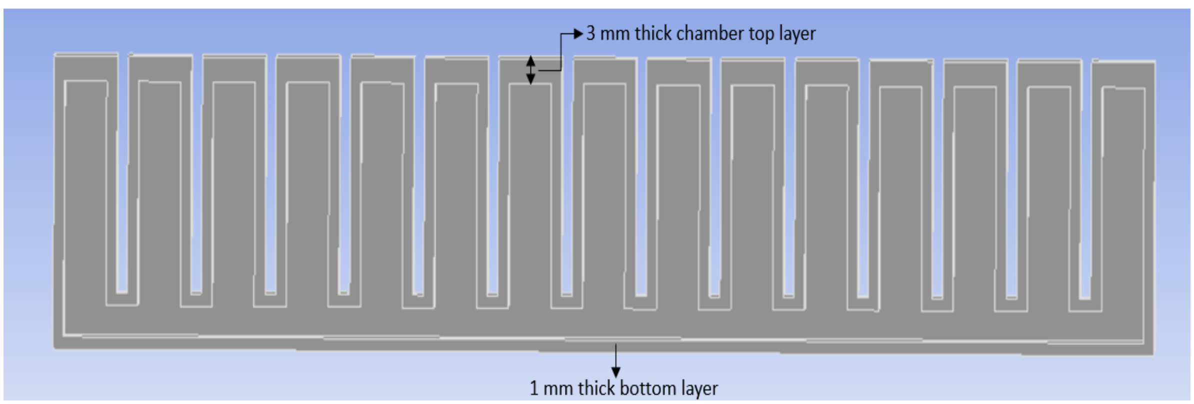


Fig 6: Optimized CAD model of Soft Pneumatic Actuator

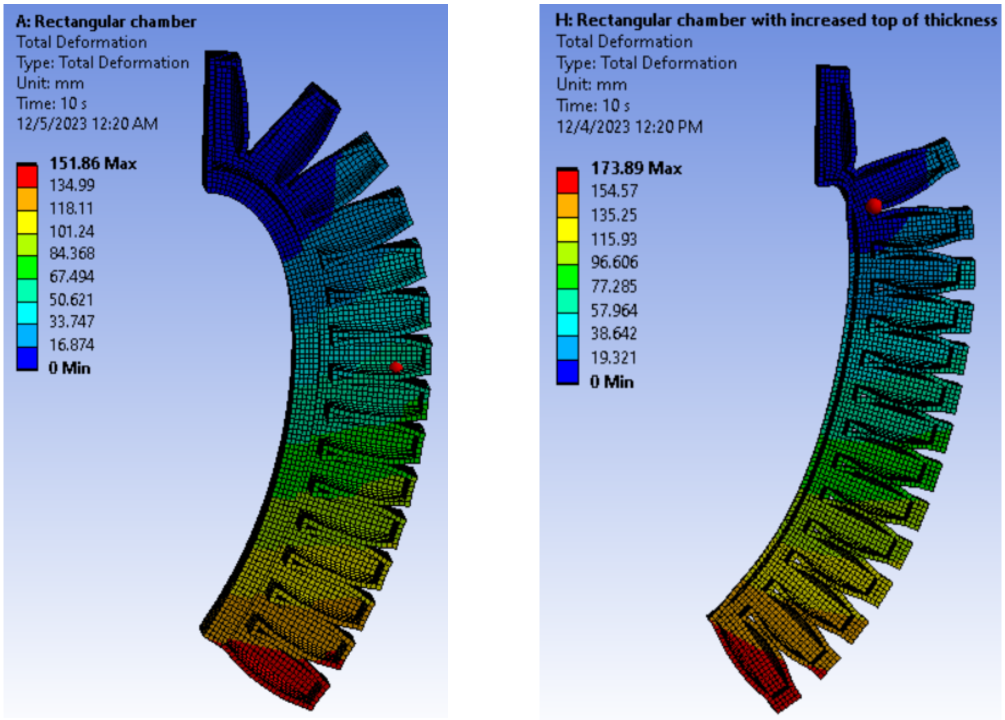
Although these parameter changes help in large bending, these parameters also have some cons. There will be an increase in stress-strain concentrations with the increase in the height of the chambers. Also, the thinner the chamber walls are, the more difficult it will be to manufacture the Soft Pneumatic Actuator.

TESTING RESULTS

The following table compares the initial design of the Soft Pneumatic Actuator and the optimised one.

	Max Equivalent Stress (MPa)	**Equivalent Strain**	**Max Total Deformation (mm)**
Initial actuator design	0.2786	0.4936	151.19
Optimized actuator design	0.2916	0.4976	173.89

Table 1: Comparison of Ansys Structural results between initial design and optimised design



(a) (b)

Fig 7: Bending in (a) Initial design and (b) Optimized design

ALTERNATE DESIGNS

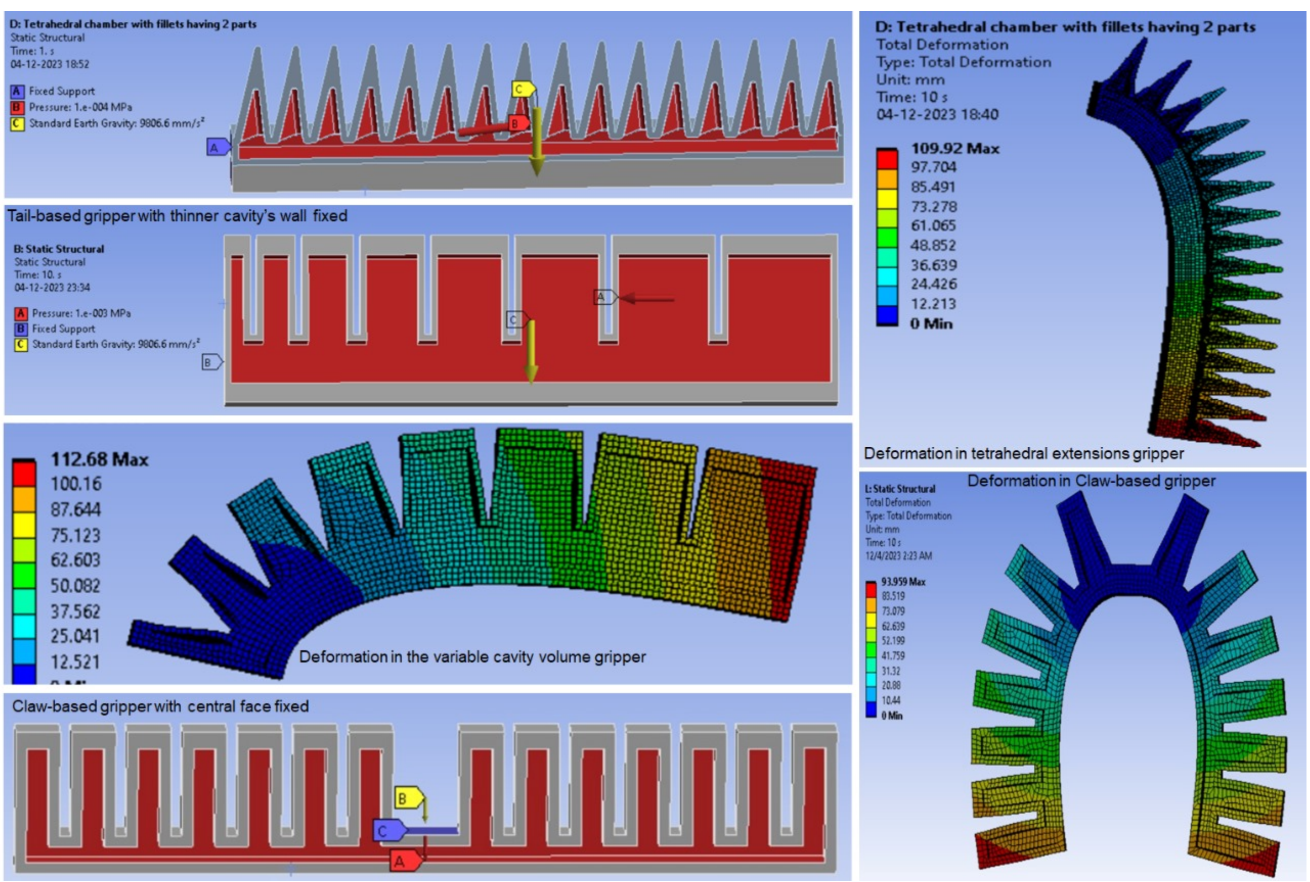


Fig 8: Alternative Designs

We have also explored alternative designs for Soft Pneumatic Actuators and observed their pros. These alternative designs are as follows:

1.) Tetrahedral chamber pneumatic actuator: In pneumatic actuators, internal chamber volume is an important parameter affecting its actuation speed. The reduction of internal chambers' volumes increases the speed of actuation[7]. Thus, we thought to use tetrahedral-shaped chambers, as among several geometric forms, tetrahedral shapes generally tend to have the least volume when considering a specific area.

2.) Tail-based pneumatic actuator: We tried to make a pneumatic actuator, taking inspiration from a vertebrate tail. We varied the thickness of the chambers to make actuators behave like their tail to observe their stability and adaptive response.

3.) Claw-based pneumatic actuator: We changed the position of input pressure and made small changes in the initial design; we got a claw-based behaviour from the pneumatic actuator. It shows how a minor change in design could bring a dynamic change in the behaviour of soft robots.

PROTOTYPE: MATERIALS AND MANUFACTURING

We will 3D print these designs and validate the simulations and accuracy of parameters we have used in FEM-based testing. Another way to manufacture this is by casting these actuators in 3D-printed moulds. Also, one of the future works in mind is to integrate this Soft Pneumatic Actuator with electro-pneumatic control[8] and make it a working prototype. We can also do experimentation with other expensive materials like Ecoflex and Dragon Skin other than silicon, and the results can be compared. Actuators based on these materials will provide greater elongation than silicon-based actuators[9].

REFERENCES

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