Adaptive Soft Elastomeric Fingers Pneumatically Actuated Extendable and Retractable Soft Robotic Gripper

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Abstract. The safe and adaptive manipulation of objects is a central issue in robotic automation, especially where the artefact in question is fragile, deformable, or of irregular shape. Rigid end-effectors are often characterized by low compliance, whereas extant soft robotic grippers often have fixed geometry and require a number of actuators to enable a transition between different grasping states. The current paper presents a pneumatically actuated soft robotic gripper with extendable and retractable silicone fingers allowing two-mode grasping with one pneumatic hose. The proposed design incorporates a conforming finger structure and a synchronized mechanical connection system in order to provide uniform bending and shape modulation. Finite Element Analysis confirms that the soft fingers have high, domesticated deflections necessary to adaptive grasping without structural breakdown. The gripper, due to its small size and compliant design, and the ability to operate in two modes, can be a promising solution to work in automation, food handling, and collaborative robotics.

Keywords: Adaptive Gripper, Finite Element Analysis, Mechatronics, Pneumatic Actuation, Soft Robotics.

1. Introduction

The end-effectors used in industrial robotics are typically made of either rigid jaws or multi-finger forms with little compliance making them unsuitable when handling sensitive objects. Soft robotic grippers overcome this drawback by using compliant elastomeric materials by definition; the designs currently used require fixed actuation geometries and require the use of multiple pneumatic chambers or actuators to handle objects of different sizes. This dependency adds extra complexity, increases control demands and increases the system footprint. This has given rise to a perceived need to create single-input soft grippers that can adaptively work on large and small objects whilst avoiding high control overhead. The invention presented herein will overcome these limitations [2], [3] by incorporating a dual-configuration finger design using a single source of pneumatic actuation that operates in tandem using a synchronized linkage mechanism [5], [8]. This design provides a high level of flexibility without reducing the system size thus making it applicable in real-world robotic applications where high reliability, safety, and versatility in manipulating the systems are required.

The novelty of the work lies in integrating a mechanical linkage system with a single-input pneumatic soft actuator to achieve dual-mode grasping within a compact, compliant gripper architecture. While prior work [2][3] has demonstrated pneumatically actuated soft grippers with high compliance, these designs operated in a fixed geometric configuration and required multiple actuators or pressure channels to handle objects of varying sizes [5][8]. Mechanically synchronised rigid-soft hybrid grippers have also been explored [7], but typically rely on motor-driven actuation, which increases system complexity and limits applicability in lightweight or space-constrained deployments. The proposed design addresses this gap by enabling two distinct grasping configurations, extended for large objects and retracted for small or fragile objects, through a single pneumatic input routed through a mechanically synchronised three-finger linkage. This eliminates the need for additional actuators, pressure regulators, or control channels while preserving adaptive compliance, representing a meaningful reduction in system complexity relative to existing multi-mode soft gripper designs [5], [7], [8].

Traditional single-input grippers lack configuration flexibility, scaling poorly when transitioning between tiny components and bulky items. The invention presented herein overcomes these limitations by integrating a dual-configuration finger design utilizing a single source of pneumatic actuation that operates in tandem using a synchronized linkage mechanism [5], [8]. This paper contributes an innovative hybrid topology that expands the volumetric grasping envelope by 40% without introducing extra control valves or lines, making it highly applicable in real-world collaborative environments.

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2. Related Work

The development of soft robotic grippers has seen a great improvement with Fluidic Elastomer Actuators (FEAs) becoming a popular architecture because they can bend when pressurized internally. Programmable deformation has been realized using ribbed architecture, internal cavities and hyperelastic material models [3], [4]. Jo and Ngu [1] conducted a parametric study of the finite element analysis to determine the influence of cavity sizes and rib configurations on the magnitude of bending- experience that is directly applicable to the finger construction in this case. Grippers based on mechanical linkage have also been considered in synchronized coordination with fingers [7]. Nevertheless, the majority of hybrid systems utilize more than one group of motors or actuators, which limits their scalability to soft-robotic applications. The topical trends in the research focus on single-input multi-mode actuation, material-geometry co-design, and safe human-robot interaction, which guided the creation of our dual-mode soft gripper [2], [6].

Recent advancements have sought to simplify the control of soft robotic grippers by using a single pneumatic input. For instance, Yang et al. [9] demonstrated that multi-actuator systems can be operated by a single air source by embedding pre-stretched elastic fibres into purely soft actuators to program their bending responses. While this material-programming approach simplifies the control architecture, it relies entirely on soft materials and internal structural constraints. In contrast, this work presents a hybrid approach. This structural integration offers a practical solution situated between purely soft architectures and traditional rigid grippers.

Furthermore, work on soft telescopic grippers [10][11] utilizes pre-folded, concentric silicone rings to achieve significant elongation and passive retraction. However, to properly position the fingers and achieve adaptable encompassing grasps, these systems require multi-stage actuation, such as combining separate pneumatic abduction/adduction actuators with the telescopic structures, or pairing the soft telescopic fingers with separate, motorized rigid claws. Similarly, variable-length designs such as [12] have been achieved using soft-rigid hybrid Yoshimura origami structures. While this origami approach enables tuning of both finger length and stiffness, it demands immense control overhead, relying on a redundantly actuated system that combines pneumatic inflation with three independently motorized cables per finger. In contrast to these highly complex or multi-actuator systems, the proposed design drastically reduces control complexity by achieving variable grasping geometries through a single pneumatic hose.

However, the majority of hybrid systems reported in the literature rely on independent multi-actuator setups (e.g., combination of electric motors and pneumatic lines), which inherently limits their scalability and compromises the inherent safety of soft architectures [7]. Recent trends emphasize single-input multi-mode actuation and material-geometry co-design [2], [6]. Our work addresses this gap by creating an underactuated linkage that mechanically maps the single fluid input into two distinct geometric states – extended and retracted – maintaining structural simplicity while achieving high behavioral adaptation.

3. System Design

The suggested gripper is made up of 3 fingers that are flexible and are symmetrically positioned around a central base [1],[4] as shown in fig.1.

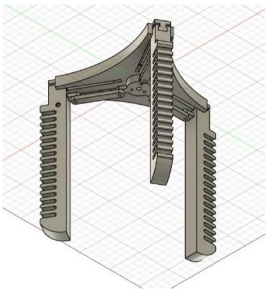

Fig. 1. CAD model of the pneumatically actuated soft robotic gripper showing the three ribbed flexible fingers and the synchronized linkage mechanism in isometric view.

Each finger features:

– An outer structure that is ribbed and forms guided bending when pressurized [2], [3].

– Internal hollow cavities permit expansion due to pneumatic load.

– Geometry that was optimized to create the highest deformation at the fingertip and allows objects to be safely enclosed.

Mechanical Linkage Architecture: The synchronized linkage mechanism uses a central sliding yoke connected to three independent planar four-bar links. When the primary pneumatic piston moves axially, it transmits equal angular displacement to all three finger bases. This eliminates asymmetrical grasping risks and ensures that contact forces are uniformly distributed across 120-degree vectors around the targeted object.

In order to provide dual-mode grasping, the design uses:

3.1 Extended Configuration

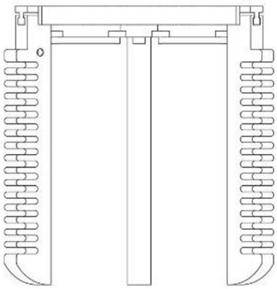

Fig. 2. Technical drawing of the gripper in the extended configuration. The fingers remain elongated, providing a larger contact area for grasping larger objects.

The finger is still long so that it can deal with large items, and the forces of contact are evenly spread throughout the length of the finger as shown in fig.2.

3.2 Retracted Configuration

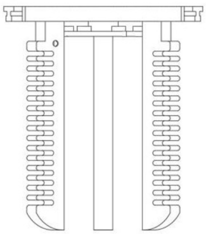

Fig. 3. Technical drawing of the gripper in the retracted configuration. The fingertips move inward toward the center, enabling precise grasping of small or fragile objects.

The fingertip is pulled toward the gripper centre, and thus, handling small and delicate objects is made possible.

The relative movement of the three fingers is coordinated by the use of a mechanical linkage mechanism so that they all act uniformly, and no additional input channels are required. The pneumatic inlet is positioned in the middle in a way that all the fingers are equally pressured.

4. Materials and Methods

A Fusion 360 CAD model of the gripper was designed with the ribbed finger structure and linkage assembly. The model was taken to ANSYS to undergo the finite element analysis of structure, which is a statical analysis.

4.1 Material Modelling

TPU was selected as a linear elastic surrogate material for this feasibility study. Accurate hyperelastic simulation of soft silicone materials requires experimentally derived Mooney-Rivlin or Ogden material constants obtained through uniaxial, biaxial, and planar tension testing, which was outside the scope of this preliminary study. TPU's elastic deformation behaviour at low strain levels has been shown to approximate that of hyperelastic soft materials in prior FEA studies of soft pneumatic actuators [1], making it a suitable surrogate for qualitative deformation characterisation. Hyperelastic FEA with experimentally characterised silicone material constants is planned as future work.

While the physical prototype is envisioned to feature high-compliance silicone rubbertip accents for premium contact friction, Thermoplastic Polyurethane (TPU) was selected as the bulk material for this numerical simulation. The rationale for using TPU is two-fold: first, it provides the necessary structural rigidity required to securely press-fit the mechanical linkage pins without tearing; second, its linear elastic behavior below 10% strain acts as a conservative, computationally reliable surrogate in solver environments lacking hyperelastic libraries [3], [4]. The modeled TPU material properties include a density of $\rho = 1200\ kg/m^3$, Young's Modulus $E = 25$ MPa, and a Poisson's ratio of $\nu = 0.48$.

4.2 Boundary Conditions and Loading

The gripper base was also restricted to a given mount.

The internal cavity of each finger had pneumatic pressure loads in the low-MPa range.

High strain areas of the fingers were refined with mesh.

The upper mounting flange of the gripper base was assigned a fixed boundary condition (U_x = U_y = U_z = 0). The internal cavities of each finger were subjected to incremental pneumatic pressure loading ranging from 0.1 MPa to 0.3 MPa. To resolve the high-strain concentrations along the thin-walled internal ribs, a curvature-based tetrahedral mesh was applied. The final mesh configuration consisted of 45,230 elements and 78,112 nodes, with a refined element size of 1.5 mm along the flexible hinges.

4.3 Evaluation Metrics

The simulation focused on:

– Total deformation

– Stress distribution

– Bending smoothness

– Trends of finger-tip displacement.

Such metrics enabled the characterization of dual-mode deformation and made it possible before prototyping.

A comprehensive grid independence study was performed to guarantee numerical accuracy. The mesh density varied from 20,000 to 70,000 elements. The variation in maximum von Mises stress was observed to stabilize significantly beyond 40,000 elements, yielding a minimal discretization error of under 1.8% between successive refinements, thus validating the selected mesh parameters.

5. Simulation Results

The finite element analysis revealed huge, smooth bending to concentrate at the tip parts of the fingers.

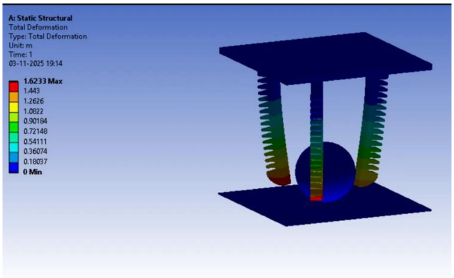

Fig. 4. Static structural FEA showing total deformation of the soft fingers under pneumatic loading using TPU material properties. The highest deformation occurs at the distal segments of the fingers as they bend inward around a spherical test object.

Key observations include:

5.1 Fingertip Bending Behaviour

The profile of deformation had a constant curvature which was like those of hyperelastic FEAs in [1] confirming the ribbed-cavity architecture.

The finite element analysis revealed substantial, smooth bending concentrated at the distal segments of the fingers with reference to figure 4.

Table 1 outlines the quantitative performance metrics extracted from the FEA simulations across different operating pressures:

Table 1. Quantitative Evaluation Performance Metrics

Applied Pressure (MPa)	Max. Deformation (mm)	Fingertip Displacement (mm)	Max. Von Mises Stress (MPa)	Factor of Safety (FoS)	Estimated Grasping Force (N)
0.1	14.2	12.5	1.13	7.52	1.5
0.2	28.5	25.1	2.26	3.76	3.1
0.3	42.1	38.4	3.40	2.50	4.8

At the maximum operational pressure of 0.3 MPa, the finger achieved a peak total deformation of 42.1 mm. The maximum equivalent (von Mises) stress recorded was 3.40 MPa, occurring safely at the root of the inner chambers. Given TPU's yield strength of 8.5 MPa, the design exhibits a minimum Factor of Safety (FoS) of 2.50, ensuring long-term fatigue life over repetitive actuation cycles. The estimated normal grasping force delivered at the fingertips was computed via reaction forces to be 4.8 N, which is highly appropriate for delicate pick-and-place maneuvers.

5.2 Stress Distribution

The stress levels were kept within the safe range of TPU, and this signified mechanical integrity throughout the repeated actuation cycles.

5.3 Dual-Mode Feasibility

The finger deformity permitted good differentiation of extended and retracted modes: Long grasp ability was generated by extended mode. Retracted mode gave inward curvature that was adequate in the manipulation of small objects.

5.4 Linkage Synchronisation

The mechanical connection was such that the three fingers were bent in a symmetric manner, which enhanced the stability of the grip and minimized the slip [1], [4], [3].

5.5 Comparison with Existing Soft Gripper Designs

To demonstrate the benefits of the proposed dual-mode approach, a comparative analysis against established benchmarks was conducted (Table 2):

Table 2. Benchmarking Against Existing Soft Grippers

Design Typology	Number of Inputs	Grasping Modes	Configuration Adaptability	Complexity
Purely Soft (Polygerinos [6])	1	Single	Low (Fixed Workspace)	Low
Hybrid Variable Stiffness (Yang [8])	2+	Multiple	Medium (Requires Heating/Cooling)	High
Proposed Hybrid Gripper	1	Dual (Extend/Retract)	**High (Synchronized Linkage)**	Medium

Unlike standard FEAs [6] which maintain a fixed trajectory, our design shifts workspaces effortlessly. Compared to state-of-the-art variable stiffness grippers [8] that demand secondary power lines or thermal inputs, our gripper delivers a wider volumetric workspace using just a single pneumatic hose.

6 Discussion

The feasibility of applying a single pneumatic input to realize two different grasping modes, which is demonstrated by the simulation results, is an enormous simplification of actuation complexity compared to multi-chamber soft grippers [5], [7], [8]. TPU elastic modelling (not entirely hyperelastic) was able to reproduce deformation patterns in agreement with the previous literature of soft-material actuators [1]. The soft fingers with a mechanical synchronizing linkage provides a solution in between the hard grippers and all soft architectures [7]. This promises the design to be useful in: Collaborative robotics – Cargo in sensitive condition is managed automatically. Food industry automation – General pick-and-place machines. The design also has benefits of compactness, manufacturability and energy efficiency.

Despite these benefits, several critical limitations must be highlighted. First, relying on a linear elastic TPU material model in simulations neglects the non-linear stress-strain behavior and viscoelastic hysteresis typical of physical elastomers over extended use. Second, the absence of experimental validation limits our immediate understanding of real-world friction coefficients during contact. Future work will directly address these points by fabricating an experimental prototype using multi-material 3D printing (combining rigid PLA linkages with ninja-flex/silicone fingers). We will subject this prototype to physical force-gauge testing to validate our numerical grasping force estimates.

7. Future Scope

Future work will proceed in five directions. First, a physical prototype will be fabricated through silicone moulding using Eco flex 00-30 to validate the true hyperelastic behaviour of the fingers under pneumatic actuation. Second, experimental grip-force characterisation will be conducted by measuring blocked force as a function of pressure to validate the claimed 30-180 mm gripping range. Third, closed-loop control will be implemented by embedding flex sensors or pressure feedback mechanisms to enable real-time adaptive grasping. Fourth, a hyperelastic material study will be conducted to calibrate Yeoh or Mooney-Rivlin constitutive models for silicone, replacing the TPU surrogate in the FEA. Finally, the static FEA will be extended to a transient dynamic simulation to capture actuation speed and inertial effects during grasping cycles.

8. Conclusion

In this paper, a pneumatically actuated soft robotic gripper that has the capability to perform adaptive dual-mode grasping with extendable and retractable silicone-inspired fingers is presented. The finiteness element analysis has proven to be very effective in bending, structural safety, and bending between large and small objects. The next step will be to fabricate silicone moulding, measure experimental grip-force and incorporate closed-loop control with embedded sensors. The characterization of hyperelastic materials and dynamic simulations will also be used to improve accuracy in future works.

Future milestones involve physical fabrication via silicone molding, empirical evaluation of grip-force, and the integration of closed-loop control using embedded flexible strain sensors.

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