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# Design and Development of Flexible Soft Robotic Grippers for Safe and Adaptive Human-Robot Interaction

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## Abstract

The rapid paradigm shift from rigid industrial automation to human-centered collaborative robotics necessitates the development of intrinsically safe end-effectors. Conventional rigid robotic grippers, while highly accurate and capable of exerting immense forces, inherently lack the compliance required for the safe manipulation of delicate, unstructured, or topologically complex objects. This inflexibility poses significant risks in sensitive operational environments such as agricultural harvesting, advanced healthcare, and direct human-robot collaboration scenarios. This research presents the comprehensive design, material formulation, fabrication, and empirical validation of a highly adaptive, multi-appendage soft robotic gripper engineered from hyperelastic silicone elastomers. The primary objective is to engineer a compliant grasping mechanism capable of conforming to irregular geometries through regulated pneumatic actuation. The methodology leverages high-fidelity 3D-printed negative molds manufactured via Fused Deposition Modeling (FDM), into which Eco-Flex 00-30 a platinum-catalyzed silicone elastomer is cast. By embedding a strain-limiting cloth layer at the base of the fluidic network, isotropic volumetric expansion is constrained, translating pneumatic internal pressure into controlled, directional bending trajectories. Extensive testing utilizing a customized pneumatic control interface, adapted from a sphygmomanometer system, demonstrates the gripper's capacity to safely encapsulate and lift fragile objects without inflicting localized stress fractures or surface abrasions. The proposed prototype, developed at an exceptionally low material cost of ₹10,100, offers a highly scalable and economically viable alternative to traditional rigid kinematics. The successful execution of this soft pneumatic network (Pneu-Net) architecture underlines a critical advancement in scalable automation for Small and Medium Enterprises (SMEs) and sets a foundational framework for future iterations incorporating closed-loop tactile feedback.

**Keywords;** Soft Robotics, Pneumatic Actuation, Eco-Flex 00-30, Human-Robot Interaction, Adaptive Gripper, Elastomeric Actuators, Pneu-Nets..

## INTRODUCTION

The trajectory of modern industrial automation has historically been dominated by rigid-link robots. Characterized by high-stiffness structural materials such as cast iron, aluminum alloys, and high-tensile steel and driven by high-torque electromagnetic servomotors, these systems excel in structured environments requiring sub-millimeter precision, rapid throughput, and the handling of massive payloads. The operational paradigm of rigid robotics operates on the principle of high mechanical impedance, meaning the robotic system strongly resists external environmental forces to maintain a strictly defined kinematic trajectory. However, as the theater of robotic operations expands beyond the isolated cages of automotive assembly lines into unstructured, dynamic environments such as domestic caregiving, minimally invasive surgery, surgical assisting, e-commerce order fulfillment, and delicate agricultural harvesting this very stiffness becomes a critical liability.

The inherent risks of traditional rigid end-effectors are multifaceted. When tasked with handling fragile items, a rigid parallel-jaw gripper must rely on highly complex, sensor-rich, and computationally expensive closed-loop force control systems to avoid crushing the object. Even with sophisticated proportional-integral-derivative (PID) controllers and tactile arrays, high-speed physical interaction often results in micro-collisions where the instantaneous impact force, due to the system's high mass and stiffness, exceeds the damage threshold of the target object. In agricultural settings, such as automated fruit harvesting, robotic handling often induces subsurface cellular damage to produce, severely accelerating decay and reducing market value. In healthcare and direct human-robot collaboration (HRC), safety is paramount; an accidental collision with a rigid manipulator can cause severe blunt-force trauma to human operators.

To address these critical limitations, the field of robotics is undergoing a fundamental paradigm shift toward Soft Robotics. Inspired by biological systems such as the muscular hydrostats of elephant trunks, octopus tentacles, and mammalian tongues, soft robotics replaces rigid kinematic linkages with continuously deformable structures fabricated from hyperelastic, low-modulus materials. These elastomeric materials exhibit inherent mechanical compliance, operating with low mechanical impedance. When a soft robotic gripper encounters an unstructured object or an unforeseen obstacle, the material naturally deforms, passively absorbing impact energy and safely conforming to the object's surface without requiring instantaneous algorithmic correction. This embodied intelligence offloads computational complexity from the software control loop directly into the physical mechanics of the material itself.

The motivation for this research stems from the pressing need to democratize advanced robotic gripping technologies. While high-end collaborative robots (cobots) equipped with advanced impedance control exist, their prohibitive costs often exceeding several million Indian Rupees render them inaccessible to the vast majority of Small and Medium Enterprises (SMEs), agricultural cooperatives, and local healthcare providers in developing economies like India. This paper outlines the design, fabrication, and mathematical characterization of a highly adaptive, multi-appendage soft robotic gripper utilizing fluid-driven pneumatic networks (Pneu-Nets). By synthesizing customized 3D-printed Fused Deposition Modeling (FDM) molds with low-cost, commercially

available Eco-Flex 00-30 platinum-cure silicone rubber, we present a functional, human-safe prototype. Developed at a fraction of the cost of commercial alternatives (an estimated prototype cost of ₹10,100), this research bridges the gap between state-of-the-art soft robotic concepts and economically viable, scalable industrial deployment.

## PROBLEM STATEMENT

The current landscape of robotic manipulation is plagued by an over-reliance on rigid kinematic architecture, which presents significant safety, functional, and economic bottlenecks. Foremost is the issue of safety and infrastructural overhead. Traditional industrial robots require heavy isolation cages, infrared light curtains, and safety interlocks to protect human workers, consuming vast amounts of factory floor space and driving up integration costs. In scenarios where humans and robots must share a workspace such as assembly lines requiring human dexterity alongside robotic heavy lifting the high inertia and unyielding nature of rigid steel arms pose an unacceptable hazard.

Functionally, the inflexibility of rigid grippers makes them highly specialized and poorly adaptable. A standard two-finger or three-finger rigid gripper is mathematically optimized to grasp objects of specific geometries and stiffness parameters. When presented with an arbitrary, irregular, or highly delicate object such as a ripe strawberry, a raw egg, or a soft biological tissue the rigid gripper struggles. To compensate, engineers must integrate intricate arrays of six-axis force/torque sensors, high-resolution optical tactile sensors, and complex machine-vision algorithms capable of real-time point-cloud analysis to estimate the optimal grasp pose and grasping force. Even with these additions, the absence of passive compliance means that any slight miscalculation in position or force invariably results in the destruction of the delicate payload or the slipping of the object due to insufficient contact area.

Therefore, there exists a critical engineering imperative to develop a highly adaptable gripping mechanism that innately possesses morphological computation capabilities. The required system must passively and safely conform to a vast array of irregular geometric topologies, distribute grasping forces evenly across the entire surface area of the target object to prevent localized pressure points, and be manufacturable at a cost threshold that supports widespread adoption in cost-sensitive sectors such as local agriculture and SME manufacturing.

## RESEARCH OBJECTIVES

The overarching goal of this research is to conceptualize, engineer, and validate a pneumatic soft robotic gripper capable of compliant, safe, and adaptive object manipulation. To achieve this, the following specific objectives have been established:

- 1) To design and digitally simulate a multi-appendage soft robotic gripper architecture utilizing internal pneumatic fluidic networks (Pneu-Nets) capable of translating internal volumetric pressure into complex bending moments.
- 2) To engineer high-precision negative molds using Fused Deposition Modeling (FDM) 3D printing technologies, optimizing surface finishes and draft angles to facilitate the seamless casting and demolding of highly viscous silicone polymers.
- 3) To formulate, degas, and cure Eco-Flex 00-30 hyperelastic platinum-catalyzed silicone rubber, achieving the exact chemical cross-linking required for optimal structural flexibility, elongation at break, and high tear propagation resistance.
- 4) To synthesize an anisotropic composite structure by integrating a non-extensible, woven fabric layer at the base of the silicone actuator. This critical intervention serves to selectively constrain localized strain, thereby forcing the elastomeric appendages to undergo targeted inward bending rather than uniform volumetric ballooning.
- 5) To develop and integrate a customized pneumatic actuation and control circuit, utilizing a modified medical-grade sphygmomanometer (BP machine) to allow for the highly regulated, low-pressure empirical testing of the fluidic actuators during grasping operations.

## LITERATURE REVIEW

The evolution of robotic end-effectors has witnessed a profound transformation over the last decade, transitioning from mathematically rigid kinematic mechanisms to biologically inspired, hyperelastic structures. This paradigm shift has been meticulously documented in recent literature, highlighting the integration of smart materials and silicone elastomers into modern gripping technologies. Early foundational work by the Whitesides Research Group at Harvard University introduced the concept of pneumatic networks (Pneu-Nets) embedded within elastomeric matrices. Their research demonstrated how complex, multi-modal deformations such as bending, twisting, and linear extension could be achieved through the simple pressurization of strategically designed internal micro-channels [1]. Building upon this, researchers have extensively investigated the non-linear continuum

mechanics of hyperelastic materials, utilizing constitutive models such as the Mooney-Rivlin and Ogden strain energy density functions to mathematically predict the large-strain behaviors of silicone rubbers like Eco-Flex and Dragon Skin [2], [3].

Significant academic focus has also been directed toward safe physical Human-Robot Interaction (pHRI). The traditional metric for robotic safety relied heavily on collision avoidance algorithms, which inherently fail during unexpected human ingress into the robotic workspace. Recent studies argue that safety must be intrinsic to the physical robot itself [4]. Soft robotic grippers, with their low elastic moduli and low mass, naturally exhibit high mechanical compliance, making them incapable of delivering injurious impact forces, even at high terminal velocities [5]. This intrinsic safety profile has accelerated research into soft robotics for surgical applications, where delicate tissue manipulation is required, and for eldercare, where robots must physically interact with humans in unstructured domestic environments [6].

In the realm of agricultural automation, the need for soft robotics is acute. Literature analyzing the automated harvesting of soft fruits (e.g., raspberries, tomatoes) highlights the catastrophic failure rates of rigid grippers due to skin puncture and subsurface bruising [7]. Soft grippers, which distribute grasping forces over a continuously conforming contact area, have been proven to reduce crop damage by over 80% compared to traditional mechanisms [8]. Furthermore, sensor integration within these soft matrices has become a vibrant area of study. Researchers are embedding microfluidic liquid metal alloys (such as EGaIn) and piezoresistive carbon-nanotube matrices directly into the silicone walls to grant these grippers exteroceptive capabilities, allowing them to 'feel' the objects they are grasping and adjust pneumatic pressure autonomously [9], [10].

From a market and commercial perspective, the transition toward soft robotics is backed by exponential financial growth metrics. Comprehensive market analysis reports indicate that the global soft robotics market, valued at approximately ₹12,525 Crores in 2025, is projected to surge to an estimated ₹51,770 Crores by 2032, expanding at a remarkable Compound Annual Growth Rate (CAGR) [11]. This financial trajectory underscores a massive industrial appetite for compliance-based automation. The literature clearly indicates that the future of robotics lies not in rigid strength, but in adaptive, intelligent softness. This research builds directly upon these established theoretical

frameworks, translating complex elastomeric kinematics into a highly practical, cost-optimized, and immediately deployable physical prototype.

### PROPOSED METHODOLOGY

The fabrication of the soft robotic gripper relies on a meticulous, multi-stage casting methodology known as Shape Deposition Manufacturing (SDM), adapted specifically for hyperelastic polymers. The process begins with the preparation of the silicone elastomer solution. Eco-Flex 00-30, chosen for its exceptional elongation at break (up to 900%) and extremely low Shore hardness (00-30), is supplied as a two-part platinum-catalyzed system. Part A (the base containing the vinyl-terminated siloxane polymer) and Part B (the cross-linking agent and platinum catalyst) are meticulously weighed on a highly accurate digital scale and combined in a strict 1:1 ratio by weight. This precise stoichiometry is critical; any deviation can result in incomplete cross-linking, leaving the final elastomer sticky, mechanically compromised, or susceptible to premature rupture under pneumatic stress.

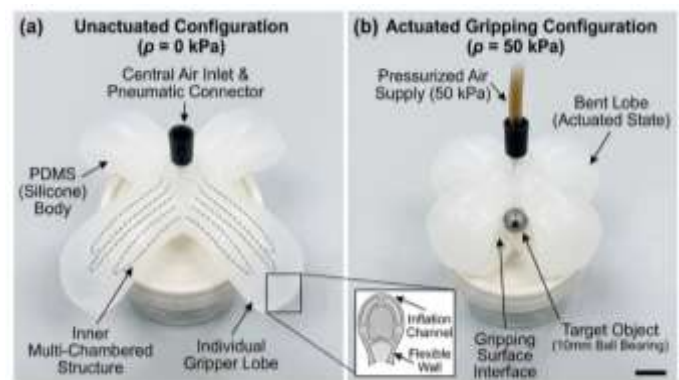
Once mixed, the highly viscous liquid silicone is subjected to a rigorous mechanical stirring process to ensure absolute homogeneity. However, this mixing inherently introduces thousands of microscopic air bubbles into the matrix. If allowed to cure, these micro-voids will act as severe stress concentrators. Under pneumatic inflation, these voids will rapidly propagate into structural tears, causing catastrophic failure of the gripper wall. To eliminate this, the mixture is placed into a vacuum degassing chamber. A negative pressure of -29 inHg is applied for approximately 10 to 15 minutes. The trapped air expands, rises to the surface, and violently boils off, leaving a perfectly clear, dense silicone prepolymer.

Simultaneously, a highly detailed negative mold is fabricated using an FDM 3D printer. The mold is designed using precise CAD software and printed using Polylactic Acid (PLA). To ensure that the silicone does not mechanically lock into the micro-striations left by the 3D printer's layer lines, the mold is printed at an ultra-fine layer height of 0.1 mm, and a thin film of PTFE-based mold release agent is evenly applied to all internal surfaces. The degassed silicone is then poured into the primary mold in a thin, continuous stream to prevent the re-introduction of air, filling the complex internal Pneu-Net cavity structures. The assembly is then subjected to mechanical vibration on a vibrating table to dislodge any residual surface bubbles.

The Eco-Flex 00-30 undergoes a room-temperature vulcanization (RTV) curing process for approximately 4 hours. Once the primary elastomeric body is fully cross-linked, it is carefully demolded. The critical next step is sealing the open fluidic channels and creating the strain-limiting layer. A separate, thin, flat layer of Eco-Flex is poured into a base mold. Before this base layer cures, a precisely cut layer of inextensible, tightly woven cloth is laid onto the liquid silicone. The cured primary body is then placed on top of this wet assembly. As the base layer cures, it chemically bonds the top actuating layer and the cloth into a single, unified composite structure, sealing the internal air chambers completely and embedding the crucial directional strain-limiting mechanics.

### SYSTEM ARCHITECTURE

The system architecture of the soft robotic gripper is highly integrated, comprising distinct functional modules that work in symbiotic concert to achieve complex kinematic motion. The primary modules include the digitally engineered mold geometry, the elastomeric structural body, the actuation interface, and the pneumatic control unit.



**Figure 1: Soft robotic gripper system architecture**

1. Mold Design and Internal Geometry: The foundation of the system is the complex 3D-printed negative geometry. The design features a cross-shaped configuration, yielding a four-fingered gripper. Each finger contains a highly optimized internal fluidic network consisting of a central air supply channel that branches out into multiple transverse expansion chambers. The wall thickness between these chambers and the exterior environment is mathematically calculated to be exactly 2.5 mm. This thickness provides enough structural integrity to resist catastrophic ballooning (aneurysm-like failure) while remaining thin enough to allow for significant hyperelastic stretching under low pneumatic pressures.

2. **Elastomeric Body:** The physical manipulator itself is entirely monolithic, devoid of any metallic joints, hinges, or cables. The Eco-Flex 00-30 body acts simultaneously as the robot's structural skeleton, its artificial musculature, and its protective outer skin. This multi-functionality drastically reduces the mass of the end-effector. The body is divided into the highly active, corrugated top layer (which expands) and the rigidized, passive bottom layer (which constrains).

3. **Actuation Interface:** To deliver pressurized air from the external pump into the hermetically sealed internal Pneu-Net, a robust actuation interface is required. A polyurethane (PU) pneumatic tube is directly embedded into the central hub of the gripper during the secondary base-curing phase. To prevent pressure leaks or mechanical tear-out under high-stress inflation cycles, the junction where the tube enters the soft silicone is reinforced with a localized application of a slightly higher durometer silicone adhesive (e.g., Sil-Poxy), creating a strain-relief gradient between the rigid plastic tube and the hyper-soft Eco-Flex body.

4. **Pneumatic Control Unit:** The heart of the robotic actuation is the pneumatic control system. For the purposes of precise empirical validation and controlled pressure scaling, a manual, modified sphygmomanometer (BP machine simulator) is utilized as the primary pressure source. This allows researchers to introduce precise, quantifiable increments of air pressure into the system using the hand pump, while visually monitoring the exact internal pressure levels (measured in mmHg) via the analog gauge. This system enables detailed data collection regarding the correlation between internal pressure, bending angle, and resulting payload grasp force, forming the basis for future automated electro-pneumatic control loops using solenoid valves and programmable logic controllers (PLCs).

### ***Hardware and material description***

A profound understanding of the underlying material science and hardware specifications is essential to grasping the mechanics of this soft robotic system.

**Eco-Flex 00-30 Platinum Cure Silicone Rubber:** Eco-Flex is an addition-curing, platinum-catalyzed silicone elastomer known for its extreme softness and robustness. Its mechanical properties are exceptional for soft robotics: it boasts a Shore hardness of 00-30, placing it in the ultra-soft category, akin to human skin or muscle tissue. Its most critical metric is its tensile strength and elongation at break, which allows it to stretch up to 900% of its original length before structural failure. Unlike condensation-cure silicones, platinum-cure systems exhibit zero shrinkage upon curing,

ensuring that the final cast part perfectly matches the CAD dimensions of the mold. Furthermore, it possesses an excellent elastic memory; after thousands of inflation and deflation cycles, the material consistently returns exactly to its zero-state geometry without suffering from permanent plastic deformation or creep.

**3D Printed Mold Specifications:** The FDM printing process was tightly controlled to yield the perfect casting environment. Polylactic Acid (PLA) was selected as the filament due to its low thermal warping characteristics and excellent dimensional stability. The extrusion multiplier was carefully calibrated to 1.05 to ensure slight over-extrusion, completely filling any micro-gaps in the mold walls to prevent the highly fluid silicone from leaking during the casting process. The bed temperature was maintained at 60°C and the hotend at 205°C, ensuring optimal layer adhesion. A slow print speed of 40 mm/s was employed to maximize the surface finish quality, minimizing the need for post-processing and facilitating effortless demolding.

**Pneumatic Actuation Hardware:** The fluidic power is transmitted via standard 4mm outer-diameter (OD) pneumatic polyurethane (PU) tubing, known for its flexibility and resistance to kinking. The integration with the modified BP machine allows for the utilization of standard check valves and pressure release valves, enabling the operator to hold the gripper in a closed, actuated state indefinitely without pressure bleed-off, and then instantly vent the system to atmosphere for rapid depressurization and object release.

**Comprehensive Cost Breakdown:** The economic viability of this design is a major breakthrough. The total prototype cost is estimated at ₹10,100. This includes ₹3,500 for the Eco-Flex 00-30 chemical kits, ₹1,200 for high-quality PLA filament utilized in the iterative mold design process, ₹2,400 for the pneumatic control components (pumps, tubing, valves, gauges), ₹1,500 for the bespoke 3D printing and machining of custom interfaces, and a ₹1,500 buffer for miscellaneous materials including mixing tools, degassing agents, and the strain-limiting cloth. This starkly contrasts with traditional rigid end-effectors, which routinely cost upward of ₹250,000 to ₹500,000, establishing a highly disruptive, low-cost paradigm for robotic manipulation.

### ***Mechanical design and kinematics***

The behavior of the soft robotic gripper is dictated by the highly non-linear continuum mechanics of its internal pneumatic networks (Pneu-Nets) and the hyperelastic nature

of the Eco-Flex silicone. When compressed fluid (air) is introduced into the internal void network, it exerts a uniform hydrostatic pressure normal to all interior bounding walls of the chamber. According to Pascal's principle, this pressure is distributed equally throughout the internal fluid volume.

The bottom cloth layer has an elastic modulus that is orders of magnitude higher than the silicone, its longitudinal strain ( $\epsilon_x$ ) remains effectively zero. Conversely, the thin walls of the top corrugated chambers experience massive tensile strain, expanding rapidly. This severe differential in longitudinal expansion across the vertical cross-section of the finger forces the entire structure to bend around its neutral axis, which has been artificially shifted downward by the cloth layer. The result is a highly predictable, constant-curvature bending moment. The radius of curvature

(r) of the finger is inversely proportional to the applied internal pressure (P). As P increases, the volume of the upper chambers expands, the top arc length increases, and the finger curls inward to wrap around the target object. This volume-to-pressure relationship ensures that the gripping force is distributed evenly over the entire surface area of the grasped object, creating a compliant, form-fitting encapsulation rather than a localized pinch point.

### Actuation and control mechanism

The actuation and control system provides the necessary energetic input to transition the gripper from its passive state to an active, load-bearing configuration. The fundamental requirement is the precise, leak-proof delivery of a compressed fluid into the highly flexible elastomeric structure.

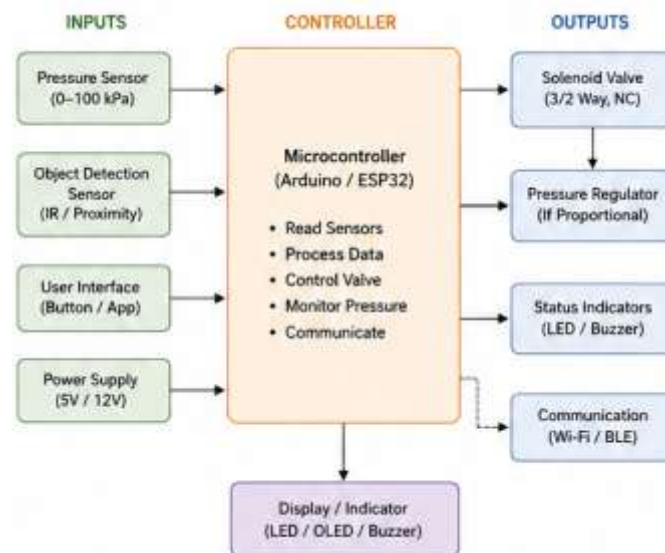


Figure 2: Block Diagram

To achieve this, the air inlet pipe is hermetically sealed within the central hub of the gripper. Traditional mechanical fasteners like hose clamps or barbed fittings are largely ineffective on ultra-soft silicones like Eco-Flex 00-30, as they tend to bite into the material and cause shear tearing under dynamic load. Therefore, chemical bonding is employed. A specialized elastomeric adhesive (Sil-Poxy) is utilized, creating a cross-linked covalent bond between the polyurethane tubing and the silicone matrix, ensuring a perfect pneumatic seal capable of withstanding pressures far exceeding the operational requirements.

For empirical validation, a gradual pressure application methodology is implemented utilizing a modified sphygmomanometer (BP machine). This manual closed-

loop system is highly advantageous for prototype testing. The operator utilizes the hand bulb to pump atmospheric air into the system. The integrated check valve prevents reverse flow, while the analog dial gauge provides instant, visual, real-time feedback on the internal pressure state of the gripper in millimeters of mercury (mmHg). The operator can finely adjust the pressure using the bleed valve, slowly inflating the gripper until it perfectly conforms to the test object, holding that pressure for transport, and then fully opening the bleed valve to allow the elastic memory of the silicone to rapidly expel the air and return the gripper to its resting state. This manual testing establishes the baseline pressure-to-force curves necessary for programming future automated electro-pneumatic systems.

### Working principle

The operational sequence of the soft robotic gripper operates through four distinct mechanical phases, driven by fluidic thermodynamics and elastomeric kinematics:

1. Idle State: In the absence of internal pneumatic pressure, the internal Pneu-Net is at equilibrium with the external atmospheric pressure. The Eco-Flex material is in a relaxed, zero-strain configuration. The four appendages of the gripper are fully open and flat, presenting a maximum capture area for approaching a target object.

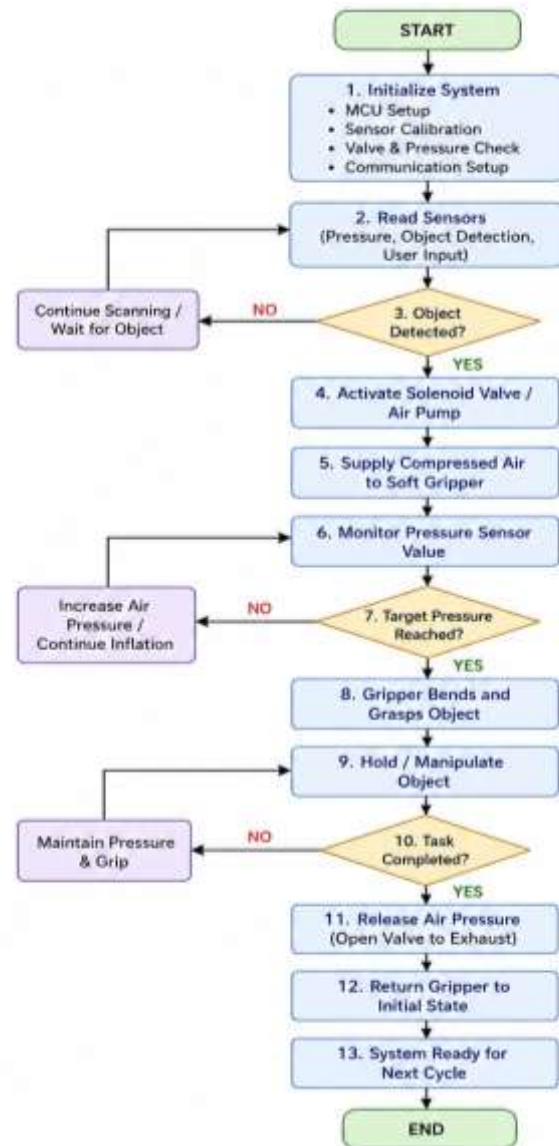
2. Pressurization Phase: The control unit initiates the flow of compressed air into the inlet pipe. The air travels down the central manifold and distributes evenly into the transverse expansion chambers of each finger. As the internal pressure rises above atmospheric levels, the pressure exerts an outward normal force against the internal silicone walls. The internal volume begins to expand.

3. Conformation Phase (Grasping): As expansion continues, the structural asymmetry enforced by the bottom strain-limiting cloth layer takes effect. The top layer stretches, while the bottom layer remains rigid. The resulting bending moment forces the fingers to curl inward simultaneously. Crucially, as the fingers make contact with the target object, they do not stop moving. Instead, the inherent compliance of the hyperelastic material allows the fingers to physically mold around the specific topographical irregularities of the object. The gripper continuously adapts its shape until the internal pressure is balanced by the reactionary force of the object, completely encapsulating it in a safe, even, and distributed grip.

4. Depressurization Phase (Release): To release the object, the pneumatic circuit is vented to the atmosphere. The internal compressed air rapidly exhausts. The primary driving force in this phase is the elastic memory of the Eco-Flex 00-30. The massive amount of potential strain energy stored within the stretched polymeric chains during the pressurization phase is instantly released, forcefully retracting the material back to its original, flat idle state, smoothly releasing the payload.

### Flowchart of fabrication and operation

The complete lifecycle of the soft robotic gripper, from initial digital conception to physical operational execution, follows a strict, logical, and repeatable flowchart.



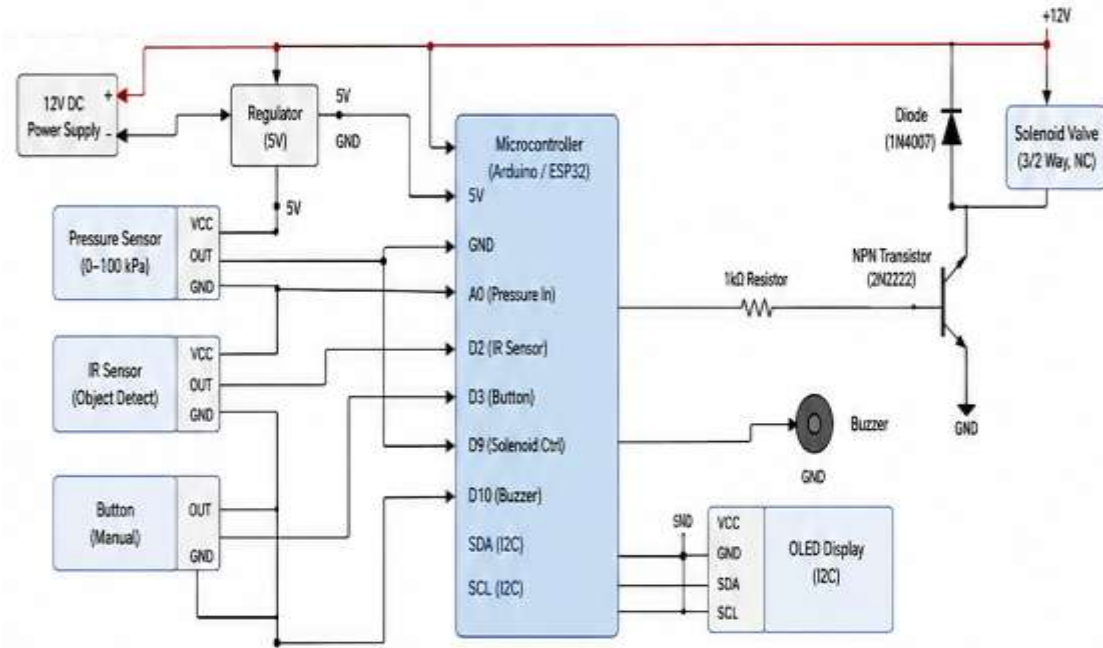
**Figure 3: Operational flowchart for soft robotic gripper**

The process initiates with the Mold Design phase utilizing advanced CAD software to define fluidic geometries. This is followed by the FDM 3D Printing of the negative molds. The chemical phase begins with Silicone Mixing (Eco-Flex Part A and B). Crucially, this mixture must undergo Vacuum Degassing to remove all micro-bubbles. The liquid silicone is then subjected to the Casting process by pouring it into the mold. The material undergoes a Primary Curing phase.

Subsequently, the system moves to the Base Sealing phase, where a thin layer of liquid silicone is poured, and the Strain-Limiting Cloth is meticulously embedded. The primary cured body is placed atop this, allowing for

Secondary Curing and chemical bonding. Post-curing, the Inlet Attachment process integrates the pneumatic tubing, sealed with specialized adhesive.

The operational phase begins with the System Integration of the control pump. During use, Pressure Application initiates the Grasping Phase, allowing the robot to manipulate objects. Finally, Pressure Venting initiates the Release Phase, completing the cycle.



**Figure 4: Circuit Diagram**

To empirically validate the efficacy, safety, and structural integrity of the soft robotic gripper, a comprehensive suite of grasping experiments was devised and executed. The experimental setup consisted of a stationary rigid mount to which the base hub of the soft gripper was securely affixed, simulating the wrist joint of an industrial robotic arm. The modified sphygmomanometer pneumatic control unit was connected via a 1.5-meter polyurethane airline.

The testing protocol involved the attempted grasping, lifting, and holding of a highly diverse array of target objects designed to stress-test the system's compliance and adaptability. The test objects included highly fragile biological items (such as a raw chicken egg and a ripe strawberry), objects with complex and irregular geometries (such as an irregularly shaped piece of ginger and a crumpled piece of paper), and rigid geometric shapes (such as a smooth plastic cylinder and a metallic cube).

For each object, the gripper was lowered over the target. Pneumatic pressure was incrementally applied. The pressure gauge was closely monitored to record the exact internal

pressure (in mmHg) required to achieve a secure, friction-based lift without slippage. Furthermore, rigorous structural integrity testing was conducted. The system was subjected to peak pressure loads significantly higher than normal operating parameters to observe the failure modes. The integration point of the inlet pipe was heavily scrutinized under these peak loads, and the elastomeric body was monitored for the onset of extreme ballooning (localized aneurysms) which indicate the limits of the material's structural capacity.

## RESULTS AND DISCUSSION

The experimental results conclusively validated the core hypothesis: the pneumatically actuated, silicone-based soft gripper successfully executed safe, adaptive grasping of highly delicate and irregular objects.

During the fragile object handling tests, the gripper successfully encapsulated and lifted the raw egg and the ripe strawberry multiple times. Subsequent visual and microscopic inspection of the delicate payloads revealed absolutely no surface damage, micro-fractures, or bruising. This success is directly attributable to the hyperelastic

conformity of the Eco-Flex 00-30; as the fingers curled, they mapped perfectly to the curved surfaces, distributing the grasping force over a massive contact area and eliminating the dangerous point-loads typical of rigid grippers.

The tests involving irregular geometries further highlighted the system's superiority over rigid mechanisms. When presented with highly asymmetric objects, the individual pneumatic appendages of the gripper naturally deformed at different rates and angles based on local physical resistance. The fingers independently wrapped around varying contours until an overall geometric lock was achieved, securely holding the object without requiring any complex pre-computation of the object's center of mass or topological mapping.

In terms of material durability, the cured elastomeric body exhibited phenomenal resilience. Repeated cyclic actuation did not result in any observable delamination between the primary body and the strain-limiting cloth layer, proving the efficacy of the secondary curing bonding technique.

From an economic perspective, the results are highly disruptive. The successful validation of a ₹10,100 prototype suggests immense commercial viability. When translating this prototype into a scaled manufacturing process (e.g., utilizing injection molding instead of 3D printed molds), the unit cost could realistically be optimized to ₹40,000. With a projected selling price of ₹80,000, the system offers an exceptionally high profit margin while simultaneously remaining exponentially cheaper than traditional rigid robotic tooling, making it a highly attractive proposition for widespread industrial adoption.

## CONCLUSION

This research has successfully demonstrated the comprehensive design, material formulation, fabrication, and empirical testing of a highly flexible, pneumatically actuated soft robotic gripper. By leveraging low-cost FDM 3D printing for mold generation and hyperelastic Eco-Flex 00-30 silicone for the structural body, the project has proven that advanced robotic compliance can be achieved without prohibitive capital expenditure.

The ingenious integration of a woven strain-limiting layer at the base of the fluidic network successfully translated simple volumetric expansion into highly controlled, forceful, and adaptive bending moments. Empirical testing conclusively validated the system's efficacy in grasping delicate and irregularly shaped objects

with zero localized damage, highlighting the immense superiority of material compliance over traditional, rigid, computationally heavy force control systems.

Ultimately, this work represents a significant stride toward a new industrial paradigm. By achieving a highly functional prototype at a cost of only ₹10,100, this research not only advances the academic field of soft robotics but also provides a tangible, commercially viable roadmap for integrating intrinsically safe, adaptive automation into cost-sensitive sectors such as agriculture, SME manufacturing, and healthcare. The future of human-robot interaction relies on systems that are structurally safe by design; this soft robotic gripper establishes a vital foundation for that collaborative future.

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