A Comprehensive Review on Actuation Strategies in Soft Robotic Grippers: Pneumatic and Dielectric Elastomer Approaches

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Abstract - This paper presents a comprehensive review of recent advancements in soft robotic grippers, with a specific focus on their actuation mechanisms, design strategies, and performance evaluation. Unlike traditional rigid robots, soft grippers offer unparalleled flexibility and safety, making them highly suitable for handling delicate objects and interacting closely with humans. This review examines three critical areas of current research: the parametric study of soft pneumatic actuators using Finite Element Analysis (FEA), the development of multi-stacked Dielectric Elastomer Actuators (DEAs) utilizing backbone strategies, and the integrated design and control of multifunctional soft grippers. By analyzing these diverse approaches, this paper highlights the transition from complex pneumatic networks to advanced electroactive polymers, discussing the respective advantages in force generation, stiffness control, and structural adaptability. The findings suggest that hybridizing these actuation techniques and leveraging computational modeling are key to developing the next generation of highly adaptive robotic grasping systems.

Key Words: Soft Robotics, Pneumatic Grippers, Dielectric Elastomer Actuators (DEA), Finite Element Analysis (FEA), Actuation Mechanisms.

1.INTRODUCTION

The field of robotics is undergoing a major shift from rigid, heavy machinery to soft, highly adaptable systems. Soft robotic grippers, made from highly compliant materials like silicone and elastomers, mimic natural biological movements. This allows them to safely grasp fragile, irregularly shaped, or soft objects that traditional rigid claws would crush. Because of this, soft grippers are becoming incredibly important in industries ranging from food packaging and agriculture to biomedical engineering.

However, the main challenge in soft robotics is figuring out how to make these flexible materials move and grip with enough force and precision. This movement is called "actuation." Currently, researchers are exploring various actuation techniques to improve how these grippers bend, hold, and release objects. This paper reviews recent developments in two primary types of actuation: fluidic (pneumatic) actuation and electro-active (dielectric elastomer) actuation, alongside the computational methods used to optimize their designs.

2.Actuation Mechanism and Design Strategies

The core of any soft robotic system lies in its actuation mechanism, which fundamentally dictates how the gripper bends, exerts force, and conforms to target objects. The choice of actuator directly influences the gripper's payload capacity, response time, and overall structural complexity. Based on a comprehensive review of recent literature, the development and optimization of soft grippers can be broadly categorized into three primary domains: (1) pneumatic systems, which utilize fluidic pressure and are currently being refined through advanced computational modeling; (2) dielectric elastomer actuators (DEAs), which leverage electrostatic forces to provide compact, high-speed, and solid-state movement; and (3) holistic multifunctional designs, which focus on integrating these actuation methods with embedded sensory feedback and closed-loop control architectures. The following subsections detail the recent technological advancements and design methodologies within each of these distinct strategies.

2.1 Pneumatic Soft Grippers and FEA Modeling

Pneumatic actuation is currently the most popular method for soft grippers. These grippers have internal chambers that inflate when air is pumped inside, causing the fingers to bend inward and grasp an object. While effective, designing these chambers requires trial and error saving significant time and costs before manufacturing [1].To solve this, researchers rely on Finite Element Analysis (FEA) to simulate how different chamber shapes and wall thicknesses affect the bending and stress of the silicone material. Using software like ANSYS, engineers can predict the exact pneumatic pressure needed for a specific grip, saving significant time and costs before manufacturing.

Furthermore, FEA enables the accurate modeling of highly nonlinear, hyperelastic materials under various inflation loads. By evaluating strain energy and identifying potential stress concentration points, researchers can prevent material rupture. This computational optimization ultimately ensures higher durability, structural integrity, and a longer operational lifespan for the soft grippers.

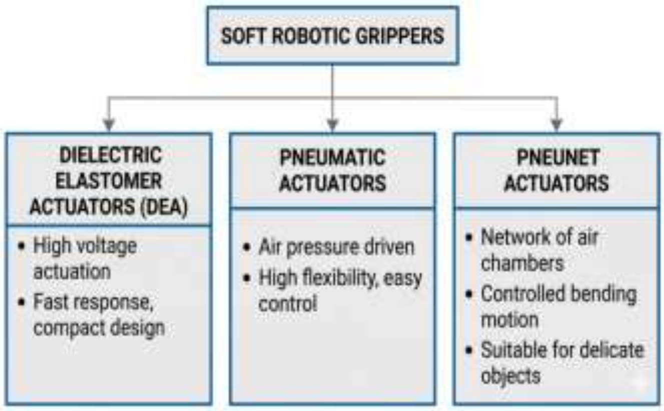

Fig -1: Structural analysis and bending simulation of a soft pneumatic actuator chamber.

2.2 Dielectric Elastomer Actuators (DEAs).

While pneumatic grippers are powerful, they require bulky air compressors and valves. To make grippers more compact and lightweight, researchers are turning to Dielectric Elastomer Actuators (DEAs). DEAs are essentially flexible capacitors; when an electrical voltage is applied, the material squeezes together and expands outward, creating movement.

A major breakthrough in this area is the use of "multi-stacked" DEAs combined with a "backbone strategy[2]." By stacking multiple layers of elastomers and integrating a flexible backbone structure, the gripper can achieve much higher bending forces and controllable stiffness. This means the fingers can be soft when approaching an object, but stiffen up securely once they make contact, behaving very similarly to a human finger.

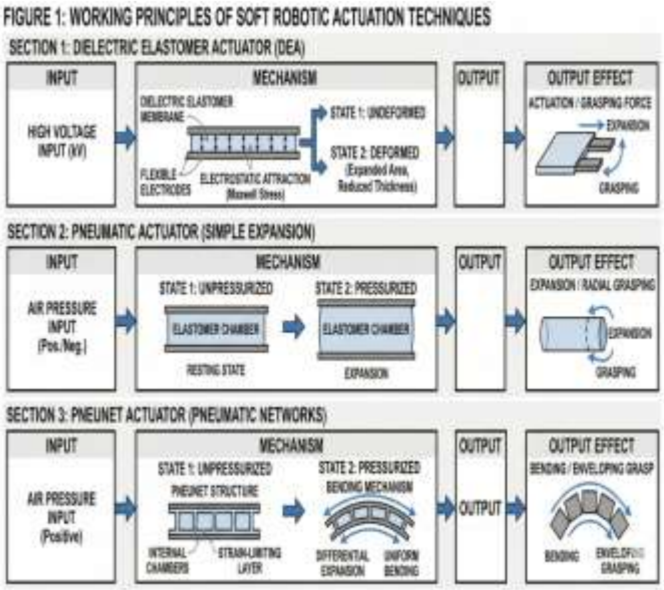

Fig -2: Architecture of a multi-stacked Dielectric Elastomer Actuator (DEA) integrated with a flexible backbone.

2.3 Integrated Design and Multifunctionality

Beyond just the actuation method, modern soft grippers are moving towards multifunctionality. This involves integrating sensors directly into the soft material so the gripper can "feel" what it is touching. Recent developments emphasize not just the mechanical design, but also the control systems required to process this sensory feedback in real-time. Testing these multifunctional grippers involves evaluating their payload capacity, response time, and durability across hundreds of grasping cycles[3], proving that soft robots are becoming reliable enough for real-world industrial applications.

2.4 Control Architecture and Sensory Feedback Integration

A critical advancement in recent soft gripper designs is the transition from open-loop to closed-loop control systems. While initial pneumatic and DEA models relied on pre-calculated inputs, modern multifunctional grippers integrate embedded sensors (such as flex sensors, tactile arrays, and pressure transducers) directly into the elastomeric matrix. This sensory feedback allows the control system to dynamically adjust the actuation force based on the physical properties of the object being grasped. Advanced control algorithms, including PID (Proportional-Integral-Derivative) controllers and neural network-based adaptive controls, process this real-time data to prevent slippage and ensure delicate handling, bridging the gap between passive compliance and active intelligence.

2.5 Performance Metrics and Fatigue Testing

Evaluating the true capability of a soft gripper requires rigorous testing protocols. Key performance metrics highlighted in recent literature include the maximum payload capacity, bending hysteresis, response time (actuation speed), and gripping force. For instance, multi-stacked DEAs are frequently tested for their maximum displacement under various voltage inputs. Furthermore, since elastomeric materials are prone to mechanical degradation, fatigue testing is essential. Grippers are subjected to thousands of continuous actuation cycles to observe material wear, micro-tearing in silicone walls, or dielectric breakdown in DEAs, ensuring they meet the durability standards required for industrial applications.

3. COMPARATIVE ANALYSIS OF ACTUATION STRATEGIES.

When designing a soft robotic system, selecting the appropriate actuation strategy is the most critical decision, as it fundamentally determines the gripper's performance, scalability, and suitability for specific applications. The ideal actuator must balance grasping force, response time, and structural complexity. Based on the reviewed literature, Pneumatic networks and

Dielectric Elastomer Actuators (DEAs) represent two of the most prominent, yet contrasting, approaches in the field. While both technologies aim to achieve life-like compliance and safe human-robot interaction, they operate on entirely different physical principles. Consequently, they offer distinct advantages and inherent trade-offs, particularly concerning power supply requirements, control mechanisms, and overall system mobility. The following comparative analysis evaluates these two systems to provide a clear perspective on their respective capabilities.

- **Pneumatic Actuators:** These excel in generating high grasping forces and significant bending angles. The use of Finite Element Analysis (FEA) has perfected their geometric designs, making them highly reliable. However, they are fundamentally limited by the need for external, bulky fluidic hardware (compressors, pumps, and valves), which restricts the mobility of the robotic system.

- **Dielectric Elastomer Actuators (DEAs):** DEAs offer a solid-state alternative with rapid response times and a highly compact form factor. The integration of a "backbone strategy" has successfully addressed their previous limitations regarding stiffness control. While they do not require bulky air pumps, they do necessitate high-voltage power supplies (often in the kilovolt range), which introduces electrical safety challenges and complex wiring requirements

Parameter	**DEA**	**Pneumatic**	**PneuNet**
Actuation Type	Electrical	Air Pressure	Air Pressure
Response Time	Fast	Moderate	Moderate
Flexibility	Medium	High	Very High
Control	Complex	Easy	Moderate
Power Requirement	High Voltage	Air Supply	Air Supply
Fabrication	Complex	Simple	Moderate
Application Suitability	Precision Tasks	General Use	Delicate Objects

Fig -3 : Comparison of Actuation

4.PRACTICAL APPLICATIONS OF SOFT GRIPPERS

The unique characteristics of soft grippers—specifically their high compliance, continuous deformation, and inherent safety—have enabled their deployment in highly complex environments where traditional rigid robotics typically fail. Unlike rigid manipulators that require precise spatial coordinates and risk damaging delicate items, soft grippers can adaptively conform to unknown, irregular shapes and absorb sudden impacts. This physical adaptability reduces the computational burden on control algorithms. Driven by recent advancements in both pneumatic networks and dielectric elastomer actuation, these soft robotic systems are rapidly transitioning from laboratory prototypes to critical real-world applications across various industries.

- **Food Processing and Agriculture:** Soft pneumatic grippers are increasingly used to handle delicate, easily bruised items like fruits, vegetables, and baked goods without causing damage.
- **Biomedical and Healthcare:** Due to their inherent safety and compliance, miniaturized DEAs and pneumatic networks are being explored for surgical retractors, rehabilitation devices, and robotic prosthetics that interact directly with human tissue.
- **Logistics and E-commerce:** In warehouse environments, multifunctional grippers equipped with sensory feedback are highly effective at sorting irregularly shaped parcels and fragile items.

5. CURRENT CHALLENGES AND FUTURE DIRECTIONS

Despite rapid advancements, several challenges remain. The primary hurdle in pneumatic systems is the miniaturization of pressure-generating components to create fully untethered robots. For DEAs, the research is heavily focused on developing new electroactive polymers that require lower actuation voltages while maintaining high energy density. Additionally, manufacturing these grippers often involves complex, multi-step molding or 3D-printing processes. Future research must address scalable, mass-manufacturing techniques to make soft robotic grippers commercially viable across all industries. The ultimate goal is the seamless hybridization of these technologies—combining the high force of pneumatics with the rapid, compact sensory control of DEAs.

3. CONCLUSIONS

The paradigm of robotic manipulation is undergoing a fundamental transformation through the development of soft robotic grippers. This comprehensive review highlights that the optimization of actuation mechanisms is the most critical factor in this evolution. Pneumatic actuation remains the industry standard for high-force, compliant grasping, with Finite Element Analysis (FEA) playing an indispensable role in refining complex chamber geometries to eliminate trial-and-error manufacturing. Conversely, Dielectric Elastomer Actuators (DEAs) represent the frontier of compact, high-speed soft robotics. The innovative use of multi-stacked architectures and flexible backbone strategies has successfully mitigated the structural limitations of DEAs, allowing for variable stiffness that mimics biological muscles.

However, the future of soft grasping does not lie in a single actuation method, but rather in integrated, multifunctional designs. The incorporation of embedded sensory feedback and closed-loop control architectures is essential for transitioning soft grippers from simple compliant tools to intelligent robotic hands. Moving forward, overcoming the challenges of untethered power supply, material fatigue, and scalable fabrication will be paramount. By addressing these hurdles, soft robotic grippers are poised to revolutionize human-robot interaction, biomedical engineering, and automated handling across diverse industries.

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