Closed-Loop Control and Perception Techniques for Soft Grippers

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Abstract. Pneumatic soft grippers have attracted considerable attention because their intrinsic compliance enables the safe manipulation of fragile and irregularly shaped objects. However, their practical performance remains constrained by challenges in structural design, proprioceptive and tactile perception, and closed-loop control. This review examines representative pneumatic actuation architectures, including PneuNet actuators, pneumatic artificial muscles, and fiber-reinforced actuators, and discusses how their structural and material characteristics govern deformation and grasping behavior. It further reviews flexible strain, pressure, optical tactile, and vision-based sensing approaches for real-time estimation of finger deformation, contact force, and incipient slip. The integration of these sensing modalities with adaptive and model-based control strategies is analyzed with respect to grasping accuracy, stability, and robustness. Finally, promising research directions are identified, including self-sensing materials, compact and energy-efficient actuators, multimodal perception, and data-driven control methods.

Keywords: Soft grippers, closed-loop control, perception technologies, pneumatic soft actuators, soft sensors

1. Introduction

The growing demand for safe, adaptive, and precise robotic manipulation has accelerated the development of soft robotics. Owing to their inherent compliance and ability to establish distributed contact, pneumatic soft grippers are particularly suitable for handling fragile, irregularly shaped, or high-value objects while reducing the risk of damage during interaction.

Despite these advantages, several challenges continue to limit the practical application of pneumatic soft grippers. First, silicone and other hyperelastic materials exhibit pronounced nonlinear deformation, viscoelasticity, and hysteresis during cyclic pressurization and depressurization, which complicate accurate dynamic modeling. Second, conventional rigid sensors are often mechanically incompatible with compliant actuators, thereby limiting the direct measurement of actuator deformation and external contact forces. Third, the manipulation of deformable objects produces continuously varying contact conditions that cannot be adequately addressed by conventional open-loop or fixed-parameter control strategies.

Addressing these limitations requires the integration of real-time perception with closed-loop control. Flexible sensor networks, tactile sensing, and visual feedback can be used to monitor deformation, contact force, and grasp stability continuously. The resulting measurements enable

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online adjustment of the actuation pressure, thereby establishing a perception-decision-execution loop that improves adaptability and robustness during grasping.

Accordingly, this paper reviews the field from four perspectives. First, the principal structures and actuation mechanisms of pneumatic soft grippers are summarized. Second, sensing mechanisms and sensor-integration strategies are examined. Third, representative closed-loop control architectures are discussed. Finally, current limitations and emerging research directions are identified, with particular emphasis on self-sensing materials, energy-efficient actuation, multimodal perception, and data-driven control.

2. Structure and Working Principle of Pneumatic Soft Grippers

Pneumatic soft grippers generally consist of elastomeric fingers containing internal air chambers. When the chambers are pressurized, asymmetric deformation of the chamber walls generates bending toward the grasping surface. In a representative multilayer design, a relatively inextensible layer constrains axial expansion, whereas a compliant chamber layer expands under pressure; the resulting strain mismatch produces the desired curvature. The deformation response is strongly influenced by wall thickness, chamber geometry, material properties, and input pressure. Compressed air is typically supplied through tubing connected to a miniature pump and regulated by valves. Upon depressurization, elastic recovery returns the fingers toward their initial configuration and releases the object. Their compliance allows pneumatic grippers to conform passively to objects of different shapes and to distribute contact forces over a comparatively large area, thereby reducing local stress concentrations and the risk of surface damage.

2.1 Structural Design of Pneumatic Soft Grippers

The structural configuration of a pneumatic soft gripper must be selected according to the required motion, payload, and contact conditions. Three representative architectures are widely reported. PneuNet actuators contain interconnected pneumatic chambers whose asymmetric expansion produces bending. Pneumatic artificial muscles generate axial contraction and relatively high force, making them suitable for applications requiring greater load capacity. Fiber-reinforced actuators incorporate nearly inextensible fibers, such as Kevlar, within an elastomeric matrix to constrain radial or axial expansion and thereby prescribe bending, extension, contraction, or twisting deformation.

Material selection is as important as structural configuration. Silicone elastomers are widely used because of their large reversible strain, ease of fabrication, and biocompatibility. Geometric parameters also have a substantial influence on performance: thinner chamber walls and larger chamber volumes generally increase deformation under a given pressure, although they may reduce load capacity and structural durability.

Consequently, the performance of a pneumatic soft gripper is governed by the coupled effects of actuator architecture, material properties, and geometric parameters. Design optimization should therefore consider these factors simultaneously to balance deformation range, blocking force, response time, durability, and fabrication constraints for the intended application.

2.2 Actuation Mechanisms and Driving Principles

Soft robotic systems may be actuated by thermal, optical, biological, magnetic, hydraulic, or pneumatic stimuli. Each approach presents distinct advantages and limitations with respect to response speed, force output, controllability, energy efficiency, and system complexity. Thermal actuation is structurally simple but generally exhibits a slow response; optical actuation can be rapid but requires line-of-sight access; biological actuation offers high compliance but involves demanding environmental requirements; and magnetic actuation enables untethered motion but requires an external magnetic-field source. For soft grippers, pneumatic actuation remains particularly attractive because it combines large deformation, a high force-to-weight ratio, straightforward fabrication, and relatively simple control hardware.

Unlike rigid grippers, pneumatic soft grippers convert internal fluid pressure directly into compliant deformation. Characterizing the relationship among pressure, deformation, and output force is therefore fundamental to actuator design, gripper configuration, and closed-loop control [1,2].

Most pneumatic soft grippers operate through pressure-induced expansion of internal chambers. Common configurations include PneuNet chamber networks, fiber-reinforced bending actuators, and bio-inspired pneumatic artificial muscles, which can generate bending, twisting, extension, or axial contraction [1-3]. PneuNet actuators produce bending through asymmetric wall thicknesses or chamber geometries. By contrast, fiber-reinforced designs constrain selected directions of expansion, thereby directing deformation along a prescribed path [3]. The appropriate configuration should be selected according to the required motion, force, workspace, and environmental conditions [2-4].

From a mechanical perspective, internal pressure deforms the elastomeric walls, typically fabricated from silicone or polyurethane, and stores elastic strain energy that drives finger motion. The large-strain behavior of these materials is commonly described using hyperelastic constitutive models, such as the Neo-Hookean, Mooney-Rivlin, and Ogden models. Geometric models additionally account for chamber arrangement, wall thickness, and fiber orientation, all of which determine whether the actuator bends, extends, contracts, or twists. Because analytical models may become inaccurate for complex geometries and contact conditions, numerical methods and experimentally identified models are increasingly combined to improve predictive accuracy.

The dynamic behavior of soft pneumatic actuators is characterized by hysteresis, rate dependence, time delay, and saturation. These effects arise primarily from material viscoelasticity, compressible-air dynamics, and friction at constrained interfaces, and they cause the pressure-curvature and pressure-force relationships to become path dependent. Consequently, a given pressure may produce different deformation or force depending on the preceding actuation history. Such nonlinearities limit the accuracy of open-loop control and motivate the use of compensation strategies, including hysteresis-aware fuzzy cascade control and model-based predictive control. Recent studies increasingly adopt a co-design approach in which actuator structure, material behavior, sensing, and control are optimized as a coupled system to improve grasp stability and repeatability.

2.3 Core Features and Application Scope

Pneumatic soft grippers are distinguished by their compliance, which enables passive adaptation to irregular geometries, tolerance of environmental uncertainty, and safer physical interaction with humans than conventional rigid grippers. Nevertheless, their performance is limited by pneumatic transmission delays, restricted payload capacity, and the difficulty of modeling large nonlinear deformation. Current research therefore emphasizes improved actuation mechanisms and integrated sensing strategies for more accurate and responsive grasp regulation [5,6].

Recent actuator designs combine origami-inspired structures with liquid-gas phase-change mechanisms to achieve multiple deformation modes. In one reported configuration, the actuator exhibits primarily axial extension below approximately 5.5 kPa and radial expansion above this threshold. This pressure-dependent transition enables two distinct motion modes within a single compliant structure while maintaining sufficient force for applications such as vascular expansion and occlusion. Origami-defined geometry can simplify fabrication and prescribe deformation without additional transmission components, thereby reducing mechanical complexity and response losses [6].

Recent studies on perception-control integration combine advanced sensing technologies with adaptive algorithms. For example, a soft gripper equipped with a liquid-lens optical tactile sensor at the fingertip achieved a response time of approximately 0.04 s, a sensitivity exceeding 0.4985 V/N, a resolution of 0.03 N, and a coefficient of determination greater than 0.96, while retaining low cost and power consumption [7]. To address nonlinear system dynamics, an adaptive force controller based on a Hammerstein model was developed. Its parameters were updated online using an adaptive law and an online sequential extreme learning machine. Simulation and experimental results demonstrated robust force tracking under nonlinear contact conditions, indicating that compact optical sensing and efficient online learning can support precise real-time force control.

3. Perception Technologies for Soft Grippers

3.1 Sensing Mechanisms

Closed-loop control requires information about both the internal state of a soft gripper and its interaction with the external environment. Flexible sensors are therefore commonly embedded in or attached to the actuator. Representative devices include graphene/PDMS strain sensors and microstructured pressure sensors, which can measure finger deformation, curvature variation, and contact pressure in real time. Their mechanical compliance minimizes interference with actuator motion, while their output signals provide feedback for state estimation and grasp regulation.

In addition to proprioceptive sensing, the spatial distribution of object-contact forces must be characterized, particularly during dynamic grasping. Optical tactile sensors provide one approach. As illustrated in Fig. 1(A) and (B), the sensor comprises an array of compliant force-sensing cells containing tracer particles. Contact-induced deformation displaces these particles, and the displacement is measured through optical triangulation. A common light source is distributed to the cells through injection optical fibers [Fig. 1(C)], while receiving fibers and a CMOS imager record the reflected-light distribution [Fig. 1(D)]. Combined with a mechanical model, the measured intensity field can be reconstructed as a three-dimensional contact-force distribution. Compared with capacitive arrays, this architecture does not require a deformable dielectric layer or a dense electrode network and is less susceptible to electromagnetic interference, which is advantageous for grasp-stability and slip assessment.

The deployment and long-term reliability of high-density sensor arrays remain challenging. To reduce sensor count while retaining useful spatial information, sparse measurements can be combined with finite-element models or deep-learning methods to reconstruct the complete deformation and contact-force fields. This strategy reduces hardware complexity and wiring requirements while preserving state-estimation capability under variable operating conditions.

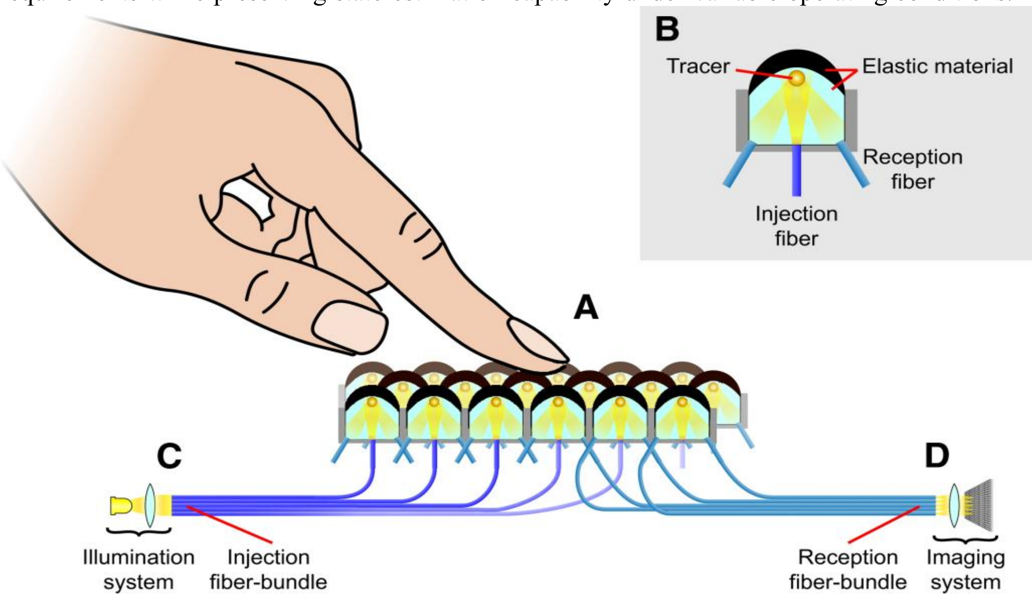

Fig. 1. Overview of the optical tactile sensor: (A) array of force-sensing cells; (B) enlarged view of a single cell; (C) light-injection system and optical-fiber bundle; and (D) imaging system and receiving optical-fiber bundle [8].

3.2 Sensor Structures and Integration

The integration of sensors into soft grippers requires simultaneous consideration of mechanical compliance, signal transmission, packaging, and durability. A typical flexible sensor comprises a sensing layer, compliant electrodes or interconnects, and protective encapsulation. These layers must remain bonded during repeated large deformation while introducing minimal local stiffness. At interfaces between soft sensors and rigid electronic components, compliant transition structures and strain-relief features can reduce stress concentrations and protect electrical connections. Sensor placement should also preserve the actuator's intended deformation mode and provide adequate sensitivity to the target variables, such as curvature, normal pressure, or shear force.

Pneumatic soft grippers require sensors that can conform to the actuator surface and withstand repeated large strains without substantially altering mechanical compliance. Reviews of flexible and stretchable sensing technologies consistently identify mechanical compatibility, signal stability, repeatability, and fatigue resistance as essential design requirements [9,10].

Flexible strain sensors are commonly classified as resistive, capacitive, or hybrid devices. Resistive sensors typically employ conductive networks composed of carbon-based fillers, metallic particles, or conductive polymers dispersed within an elastomeric matrix. Applied strain modifies the conductive pathways and therefore changes electrical resistance. Such sensors can be printed or bonded along a soft finger to measure bending and extension. Capacitive sensors instead detect changes in electrode overlap area and dielectric thickness. Stretchable electrodes combined with a compliant dielectric can provide a near-monotonic capacitance response to strain. Direct-ink writing and related additive-manufacturing methods facilitate the direct integration of both resistive and capacitive sensing elements into soft robotic structures.

Gallium-based liquid-metal alloys can be embedded within microchannels or microfluidic cavities to form highly deformable conductive elements. Because electrical continuity is maintained under large strains, these sensors can measure deformation, pressure, and contact while preserving the compliance of the surrounding elastomer. Soft-robotic sensors are often categorized according to their use in motion sensing, environmental sensing, human-robot interaction, or closed-loop control. Hybrid resistance-capacitance configurations based on liquid-metal conductors may further improve sensitivity and extend the measurable pressure range [9-11].

Contact pressure in soft grippers can be measured using embedded pressure sensors, liquid-metal microchannels, or sealed pneumatic cavities whose internal pressure varies with the applied load. Liquid-metal pressure sensors based on resistance-capacitance coupling have demonstrated sensitivity to small pressure variations over ranges relevant to contact and grasping. Combining these measurements with actuator-chamber pressure can support simultaneous estimation of finger deformation and external contact force.

Vision-based perception complements embedded tactile sensing by observing finger deformation and object contact externally or through an optical tactile interface. Marker-based systems and gel-based optical skins convert surface deformation into image features that can be associated with contact location, object pose, and force distribution [9,10]. Although such systems increase hardware and computational complexity, they provide high-dimensional information suitable for learning-based state estimation and closed-loop control.

Robust perception increasingly relies on multimodal sensing that combines strain, pressure, temperature, inertial, or visual information. Flexible sensing skins placed on or within a soft finger can simultaneously provide estimates of curvature, contact pressure, and incipient slip. The complementary nature of these measurements improves state observability and supports more reliable grasp planning and control [9-11].

Sensor integration remains challenging because embedded devices and interconnects may create local stiff regions, reduce overall compliance, and concentrate stress. Stiffness mismatch between the sensor and substrate can also cause delamination, signal drift, and premature failure under cyclic loading [9,10]. Moreover, the sensor and its wiring modify the local mechanical properties and may distort the deformation field being measured [9-12]. Consequently, recent studies emphasize the co-design of sensor layout and actuator geometry, together with calibration procedures that account for the coupled mechanics of the composite soft structure [9-12].

3.3 Functional Applications of Perception

In soft robotic manipulation, perception is not an isolated sensing function but a prerequisite for state estimation and feedback regulation. Measurements of deformation, pressure, contact force, and slip-related signals can be transformed into estimates of grasp state and subsequently used to modify actuation commands. This perception-estimation-control sequence enables pneumatic soft grippers to adapt to variations in object geometry, contact conditions, and external disturbances. Accordingly, the principal functional applications of perception include grasp-stability estimation, slip detection, shape and pose estimation, and adaptive manipulation.

For pneumatic soft grippers, the integration of sensing enables a transition from predetermined open-loop actuation to feedback-based manipulation. Sensor measurements provide information about the current grasp state, allowing the controller to update chamber pressure or finger configuration as contact conditions evolve [13]. This feedback capability is particularly important for compliant structures because large deformation and distributed contact cause the relationship between actuation pressure and grasping outcome to vary throughout a manipulation task.

A major application of perception is grasp-stability estimation. Distributed strain and pressure measurements can be used as inputs to data-driven classifiers that distinguish stable grasps from unstable or incipient-slip conditions [14-16]. Sensorized soft hands combining tactile and proprioceptive information have been evaluated with machine-learning methods for grasp-state recognition [14]. Similarly, soft grippers equipped with sensing skins have used recurrent architectures, including long short-term memory networks, to exploit temporal variations in tactile signals for grasp-success prediction [15]. These approaches indicate that time-dependent sensing information can provide early evidence of deteriorating grasp stability before gross object motion occurs [14-16].

Slip detection is closely related to grasp-stability assessment and is essential for preventing object loss while avoiding excessive gripping force. Conventional methods identify slip-related components in tactile or force signals and distinguish static contact from relative motion through signal-processing techniques [17]. Reported sensing modalities include piezoresistive, piezoelectric, optical, and vision-based tactile sensors, with both model-based signal processing and machine-learning methods used for classification [17]. More recent soft multi-axial sensors can resolve tangential loading and local deformation at the contact interface, providing feedback for rapid adjustment of gripping force [18]. Combining distributed strain sensing along the finger with pressure or shear sensing near the fingertip can therefore provide complementary information about local micro-slip and larger object displacement [17,18].

Perception can also support estimation of gripper configuration and object geometry. Distributed strain sensors and compliant sensing skins provide measurements related to finger bending and contact location, from which the deformed gripper shape and aspects of object pose can be inferred [14-16]. When strain, pressure, and visual information are combined, learning-based estimators can map multimodal measurements to object-state variables that are useful for grasp planning and subsequent control [14-16]. Such state estimates reduce reliance on nominal geometric assumptions and improve the controller's ability to respond to changes during contact.

These perception functions are especially important when object mass, friction, geometry, or contact conditions are uncertain. A feedback controller can initiate contact with a conservative actuation level and then increase or redistribute pressure in response to measured indicators of deformation, instability, or slip [14-18]. Multimodal perception is advantageous in partially observed or cluttered environments because different sensing channels provide complementary information about finger configuration and object interaction [17]. For pneumatic soft grippers, perception should therefore be treated as an integral component of the sensing-estimation-control architecture rather than as an auxiliary module added after actuator design [14-18].

4. Closed-Loop Control Design

4.1 Controller Design Approaches

Model-based control provides an interpretable framework for regulating soft robotic systems by relating actuator inputs to deformation, pressure, and output force. Among model-driven approaches, model predictive control (MPC) is particularly useful when actuator dynamics are coupled and operational constraints must be considered explicitly. In a pneumatically actuated humanoid system, system identification was used to construct a four-state model describing joint motion and dual-chamber pressure. An MPC controller operating at 300 Hz achieved accurate trajectory tracking for both single-joint and coordinated motion, illustrating the value of experimentally identified dynamic models for closed-loop regulation [19].

Proportional-integral-derivative (PID) control also remains relevant as a low-level regulation method. Real-time pressure or deformation measurements can be used to correct valve commands and reduce tracking error. In the MPC architecture reported in [19], the high-level controller generated target pressure commands, whereas a 1000 Hz PID loop regulated pneumatic pressure at the actuator level. This hierarchical arrangement illustrates how predictive planning and fast local feedback can be combined without requiring either method to operate independently.

The use of purely analytical models is nevertheless limited by large deformation, hysteresis, rate dependence, and uncertainty in contact conditions. These difficulties have motivated learning-based control methods that infer control policies or system dynamics from experimental data. Imitation learning and reinforcement learning are representative examples for contact-rich tasks in which an accurate first-principles model is difficult to obtain. However, purely data-driven methods may require substantial training data, can generalize poorly outside the training distribution, and may introduce additional safety and verification challenges.

Hybrid strategies therefore seek to combine physical structure with data-driven adaptation. Examples include model-based reinforcement learning, in which a simplified model constrains policy exploration, and learning-enhanced MPC, in which data-driven components update or compensate the predictive model during operation. Such approaches are intended to preserve the interpretability and constraint-handling advantages of model-based control while improving adaptation to unmodeled nonlinearities and disturbances. For soft grippers, the most appropriate balance between modeling and learning depends on actuator complexity, available sensing, task variability, and the amount of reliable experimental data.

4.2 Feedback Loop Implementation

A closed-loop soft-gripper architecture can be organized into three functional stages: sensing, state estimation and decision making, and actuator regulation. The controller continuously processes measurements from the gripper and updates actuation commands so that the grasp can be adjusted as the interaction state changes [20].

At the sensing stage, deformation, pressure, and tactile signals are converted into electrical or digital measurements that can be processed by the control algorithm [20]. The usefulness of these measurements depends not only on sensor sensitivity but also on calibration, repeatability, and the extent to which the sensors preserve the mechanical compliance of the actuator.

Control can then be implemented hierarchically. A low-level loop regulates quantities such as chamber pressure or finger position, while a higher-level controller coordinates multiple fingers according to task-space objectives such as grasp posture and contact force [20]. When multimodal measurements are available, the estimated grasp state can be updated continuously and used to compensate for disturbances, including changes in payload or unexpected contact events [20].

The effectiveness of the overall feedback loop therefore depends on the consistency of the complete sensing-model-control chain. High sensing accuracy alone is insufficient if the state estimator or controller does not account for actuator nonlinearities, and an advanced control algorithm cannot compensate for unreliable measurements. Co-design of sensing, modeling, and control is consequently important for achieving repeatable and robust grasp regulation.

4.3 Performance Evaluation

Performance evaluation should quantify both sensing quality and task-level closed-loop behavior. Common metrics include grasping success rate, stability under disturbances, deformation or angle-estimation accuracy, force-regulation error, and dynamic response time. Meaningful comparison also requires consistent test objects, loading conditions, and experimental procedures.

Sensor performance should be evaluated under both free deformation and object contact because the mechanical boundary conditions differ between these cases. For example, directly printable strain sensors have been evaluated through free-bending and constrained-contact experiments, and a calibrated linear model achieved a bending-angle root-mean-square error of 0.872 in the reported study [21]. Differences between free-bending and contact responses should therefore be treated as part of the calibration problem rather than as interchangeable operating conditions.

A practical evaluation framework can be organized at three levels: sensor characterization, controller verification, and task-level grasping assessment. Reporting quantitative metrics at each level makes it easier to identify whether performance limitations arise from measurement error, control design, or the physical gripper itself. Standardized benchmark objects and repeatable procedures would further improve comparability among soft-gripper systems and support assessment of reliability under realistic operating conditions.

5. Conclusion

This review examined closed-loop control and perception techniques for pneumatic soft grippers, with emphasis on actuator structure, sensing integration, feedback implementation, and performance evaluation.

The literature indicates that grasping performance is governed by the coupled effects of actuator architecture, material behavior, geometry, and sensing. PneuNet actuators, fiber-reinforced structures, and pneumatic artificial muscles provide different trade-offs in deformation mode and force output, while nonlinear material behavior and pneumatic dynamics complicate accurate modeling. Flexible strain, pressure, liquid-metal, optical, and vision-based sensors provide mechanically compatible approaches for estimating deformation and contact state, thereby enabling feedback control and slip-aware manipulation.

No single control strategy is optimal for all soft-gripper configurations. PID control remains useful for fast local regulation, model-based methods such as MPC provide explicit prediction and constraint handling, and data-driven methods can compensate for dynamics that are difficult to model analytically. Hybrid architectures that combine these approaches are therefore a promising route toward improved robustness and adaptability, provided that sensing uncertainty, model validity, and computational requirements are considered together.

Several research directions remain important. Self-sensing materials may reduce the mechanical mismatch between actuators and embedded sensors; compact and energy-efficient actuation could reduce the dependence on bulky pneumatic hardware; multimodal perception and online learning may improve state estimation under uncertain contact conditions; and standardized experimental protocols are needed for reproducible comparison across platforms. Progress in these areas will depend on tighter integration of actuator design, perception, modeling, and control rather than optimization of each subsystem in isolation.

Author Contributions

Both authors contributed equally to this work.

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