Perspective | Open Access

Soft Science

Yao et al. Soft Sci. 2026, 6, 102 DOI:10.20517/ss.2026.161

# Conducting polymer-based soft robotics

Mutian Yao[1], Gen Li[1], Liuyu Zhang[1], Qinglin Jiang[2,*], Yuguang Ma[2,*], Baoyang Lu[1,*]

**Citation:** Yao, M.; Li, G.; Zhang, L.; Jiang, Q.; Ma, Y.; Lu, B. Conducting polymer-based soft robotics. *Soft Sci.* **2026**, *6*, 102. https://dx.doi.org/10.20517/ss.2026.161

**Received:** 26 Jun 2026 **First Decision:** 5 Aug 2026 **Revised:** 15 Sep 2026 **Accepted:** 16 Sep 2026 **Published:** 12 Nov 2026

**Academic Editor:** Erika Scavetta **Copy Editor:** Pei-Yun Wang **Production Editor:** Pei-Yun Wang

Check for updates

## INTRODUCTION

Soft robotics seeks to emulate the compliance, adaptability, and safety of living organisms[1]. Unlike rigid robots with discrete joints, soft robots exploit material deformability to achieve continuous, infinite-degree-of-freedom motion and safer interaction with humans and unstructured environments[2]. These attributes position soft robotics as a transformative paradigm in biomimetic engineering, medical intervention, and exploration in confined or hazardous domains where rigid systems face operational constraints[3]. As the field moves toward deployment, developing materials and manufacturing methodologies that maintain robust, multifunctional performance under demanding conditions has become critical[4].

Conducting polymers (CPs), notably polypyrrole (PPy), polyaniline (PANI), and poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS), are attractive for soft robotic actuation[5-7]. Their electrochemical actuation via reversible redox-driven ion ingress and egress to produce volumetric change offers low operating voltages (< 1 V), high energy density per cycle, biocompatibility, and acoustic silence[8,9]. However, slow ion diffusion, moderate output stress, and reliance on liquid electrolytes still restrict bandwidth and untethered deployment. Consequently, most CP-based soft robots remain laboratory demonstrations, lacking a coherent pathway from material innovation to system-level function[10]. CPs should thus be viewed as enabling functions difficult for rigid systems rather than competitors on speed or power.

Here, CP-based soft robotics refers to systems where CPs constitute the primary functional and structural continuum of the robot body. CPs serve as the principal actuation, sensing, and energy-transducing medium, while elastomeric substrates, gel electrolytes, or structural reinforcements may be integrated as complementary elements. However, systems where CPs act only as passive conductive fillers or

[1]Jiangxi Provincial Key Laboratory of Flexible Electronics, Jiangxi Science and Technology Normal University/Nanchang Jiaotong Institute, Nanchang 330013, Jiangxi, China.
[2]Guangdong Basic Research Center of Excellence for Energy and Information Polymer Materials, State Key Laboratory of Luminescent Materials and Devices, Institute of Polymer Optoelectronic Materials and Devices, South China University of Technology, Guangzhou 510641, Guangdong, China.

*Correspondence to: Prof. Qinglin Jiang, Prof. Yuguang Ma, Guangdong Basic Research Center of Excellence for Energy and Information Polymer Materials, State Key Laboratory of Luminescent Materials and Devices, Institute of Polymer Optoelectronic Materials and Devices, South China University of Technology, Guangzhou 510641, Guangdong, China. E-mail: jiangql@scut.edu.cn; ygma@scut.edu.cn; Prof. Baoyang Lu, Jiangxi Provincial Key Laboratory of Flexible Electronics, Jiangxi Science and Technology Normal University/Nanchang Jiaotong Institute, Nanchang 330013, Jiangxi, China. E-mail: luby@jxstnu.edu.cn

externally attached sensors are excluded. Instead, we focus on all-CP, CP-composite, and CP-dominant hybrid architectures where CPs remain the functional core for actuation, sensing, energy transduction, and ultimately the integration of sensing, actuation, control, and energy function.

This Perspective assesses the current state of CP-based soft robotics and identifies four core challenges in material design, advanced processing, system integration, and application translation. To shatter these constraints and redefine CP-based soft robotics for future horizons, we formulate corresponding forward-looking directions. These include data-driven approaches for predictable CP synthesis, programmed morphogenesis for complex intelligent structures, integrated autonomy for combining sensing, actuation, control, and energy, and application-driven validation across smart healthcare, deep-sea exploration, aerospace technology, and public safety. By charting these frontiers, this Perspective aims to provide actionable guidance for accelerating the transition of CP-based soft robotics from proof-of-concept demonstrations to practical embodied-intelligence systems.

## CURRENT CHALLENGES OF CP-BASED SOFT ROBOTICS

CP-based soft robotics has advanced from materials development to fabrication methodologies, component integration, and system-level demonstrations, but these efforts still occur largely in parallel rather than collaboratively[11]. The following four bottlenecks reflect gaps between current capabilities and system-level requirements.

### The empirical synthesis bottleneck

PEDOT:PSS, PANI, and PPy offer tunable electrical properties. Composites with elastomers and nanomaterials achieve high conductivity with > 400% stretchability and toughness. Solvent systems and dynamic crosslinking enable self-healing and biodegradability, extending service life and supporting transient functions of soft robots[8,12-14]. However, CP synthesis remains dominated by empirical trial-and-error, as quantitative relationships between microstructure and macroscopic properties are incompletely captured by existing frameworks[15]. Materials design consequently proceeds through time-intensive cycles, making it difficult to explore the multidimensional performance spaces robotics requires[16]. Polymerization outcomes, including molecular weight, dispersity, doping level, and chain conformation, depend on interdependent parameters, and small variations cause significant batch-to-batch variability, making systematic exploration impractical and requiring extensive experiments to optimize a single formulation[17]. Existing CP databases have limited material types, curated data, and sharing mechanisms[18]. More fundamentally, CPs display spatial heterogeneity in chain arrangement, dopant distribution, and conductive network geometry, while characterization tools capture only local domains, creating sampling bias when linking microscale features to macroscale performance[19]. A transformative materials development methodology is needed.

### The 3D complexity bottleneck

Additive manufacturing techniques such as direct ink writing (DIW) and multi-material cryogenic printing (MCP) have produced complex 3D CP structures with ~42 μm resolution and aspect ratios exceeding 476, thereby allowing roboticists to realize functional geometries[20]. CP-based devices now include strain/pressure sensors enabling soft robots to perceive deformation and contact; low-voltage electrochemical ionic actuators for safe human-robot interaction; and electrothermal actuators for large deformation and force[21]. Nevertheless, controlled fabrication of CPs into complex 3D architectures remains challenging. DIW, cryogenic printing, stereolithography (SLA)/digital light processing (DLP), and selective laser sintering (SLS) cannot readily construct such structures. This reflects an inherent mismatch between CP chemistry and additive manufacturing physics. CPs' rigid-rod or semiflexible chains and strong π-π stacking produce rheological characteristics outside optimal printing windows, including insolubility/infusibility and

trade-offs between printable rheology and electronic performance[22]. Post-printing reorganization further alters mechanical and electrical properties[23]. Reliable multi-material integration thus requires numerous trials, calling for strategies that circumvent current layer-by-layer paradigms. Current fabrication relies on heuristic parameter tuning and lacks intelligent adaptive control and real-time defect correction[24]. Integrating data-driven process optimization is a critical missing link, as parameters including nozzle speed, extrusion pressure, temperature, and filler composition require recalibration for each new formulation or geometry[22]. Therefore, manufacturing paradigms are needed to realize complex topologies essential for functional soft robotic systems while providing the precision and adaptability of data-driven optimization.

### The integration and autonomy gap

Material-level sensing-actuation integration has been demonstrated, including a sensing-actuation system with zero signal delay, ultrafast response, and stability over 30,000 s[14], a soft robotic hand with 98.03% recognition accuracy across 20 different materials[25], and magnetic turbine robots, along with self-sensing biomimetic heart valves[20]. Despite these advances, most CP robots still depend on external power supplies or liquid electrolytes, hindering untethered autonomy. The electro-mechanical nonlinearity of CPs, device-to-device variability, and environmental sensitivity render classical control theory difficult to apply directly, often requiring individual calibration[26]. Furthermore, sensing, actuation, control, and power modules remain separate bolt-on components rather than integrated architectures, causing volumetric redundancy, energy losses, and interface issues[10]. Although physical reservoir computing (PRC) has been proposed to address this integration gap by exploiting soft-body nonlinear dynamics as a computational substrate[27], the disparity between material-level performance and system-level functionality requires architectures that fundamentally rethink the relationship between components and their integration within the CP body itself.

### The application-material mismatch

Despite this progress, CP material optimization remains poorly connected to real-world application requirements. Most studies define applications through broad labels without quantitative requirement analysis and evaluate performance under idealized laboratory conditions that differ markedly from coupled mechanical, electrochemical, thermal, and biofouling loads in actual deployment[4]. The absence of quantitative requirements leads to ambiguous material design targets; the lack of standardized performance benchmarks prevents cross-comparison between material systems; and the translation gap between idealized demonstrations and system-level applications remains insufficiently quantified[28]. The field urgently requires a systematic pathway that anchors materials development to application-driven performance metrics, addressing the full chain from requirement decomposition, translating functional needs into a quantifiable material property vector, through standardized validation protocols to validated deployment pathways bridging laboratory innovation and real-world application.

## FUTURE PERSPECTIVES

### Data-driven and predictable CP synthesis

A central pathway for future developments is transforming CP development from trial-and-error into data-driven rational design. Although p-type CPs dominate, n-type analogues such as poly(benzodifurandione) (PBFDO) expand the material design space[29]. The availability of such n-type CPs opens possibilities previously inaccessible with p-type counterparts, including complementary logic circuits[30] and ionic diodes[31]. The empirical synthesis challenges apply equally to p- and n-type CPs, and their integration into the data-driven framework will be essential for accelerating deployment. Progress requires three interconnected pathways [Figure 1A], which schematically illustrates the integrated workflow from database construction and machine learning (ML)-driven modeling to closed-loop autonomous synthesis. First, a CP Materials Genome Database should capture microstructural and macroscopic performance data across varied synthesis conditions, integrating spatially resolved multiscale characterization with explicit

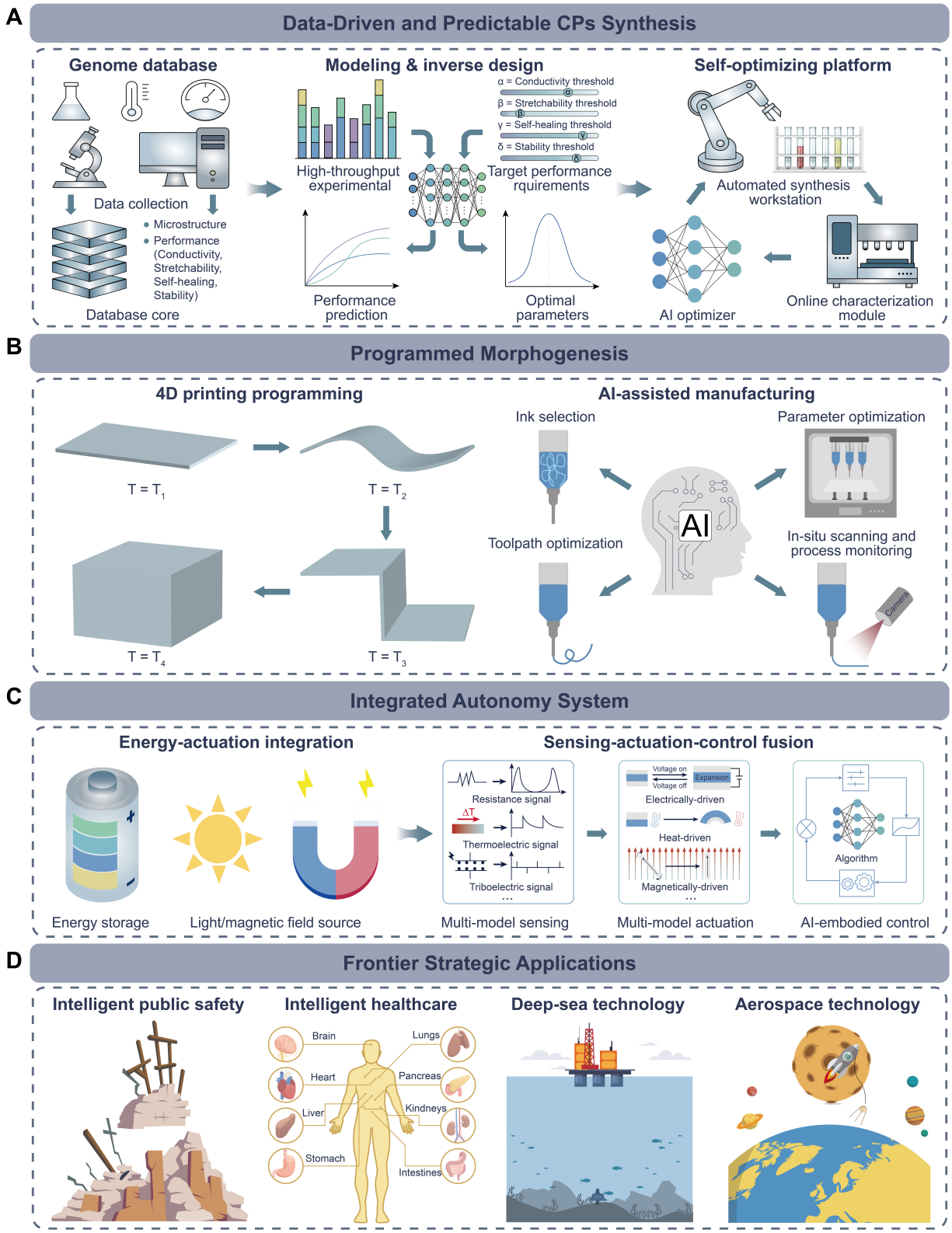



**Figure 1.** Future perspectives of CP-based soft robotics. (A) Data-driven and predictable CP synthesis; (B) Programmed morphogenesis; (C) Integrated autonomy system; (D) Frontier strategic applications. CP: Conducting polymer; AI: artificial intelligence.

uncertainty metrics. Automated high-throughput characterization and combinatorial synthesis enable systematic mapping of microstructural heterogeneity, while active learning directs sampling toward underrepresented domains[32,33]. Community data standards and open-access protocols will ensure effective data integration across laboratories.

Second, ML-driven structure-property modeling and inverse design should be implemented. ML models trained on ensemble averages from multiple localized measurements can predict macroscopic properties with confidence intervals reflecting characterization uncertainty. Among ML methodologies, Gaussian process regression (GPR) excels with small datasets[34], graph neural networks capture topological relationships[35], and ensemble methods (e.g., random forests and gradient boosting) offer robustness[36]. Applying ML to CP synthesis requires addressing multiscale structure-property relationships through hierarchical modeling integrating quantum descriptors, molecular dynamics, and experimental data[37]; high-dimensional synthesis spaces including monomer ratios, dopant concentrations, temperatures, solvents, and processing conditions[38] and probabilistic models with uncertainty quantification for polymerization stochasticity[39]. Bayesian optimization (BO) is well-suited for navigating these high-dimensional synthesis spaces by balancing exploration and exploitation to identify optimal conditions with minimal experimental iterations, as demonstrated for Pareto-optimal trade-offs between conversion and dispersity[40]. Generative models (e.g., variational autoencoders and generative adversarial networks) enable inverse design by exploring vast chemical spaces beyond conventional screening[41].

Third, a closed-loop autonomous synthesis platform should integrate automated workstations, in-line characterization, and ML optimizers into a fully automated cycle of synthesis, characterization, modeling, prediction, and iteration. Collectively, these three pathways form a cohesive pipeline: the database provides training data, ML models generate predictions and uncertainty estimates, and automated platforms execute experiments to validate and refine those predictions. Beyond immediate capability gains, this framework bridges roboticists' functional requirements and materials scientists' synthesis decisions by providing probabilistic performance predictions with quantified uncertainty, enabling both communities to operate within a common language of material performance.

## Programmed morphogenesis

Over the future horizons, the manufacturing paradigm will shift beyond layer-by-layer assembly toward programmed morphogenesis, where pre-programmed internal stress gradients make CP structures autonomously fold, twist, and buckle into complex 3D topologies under global or spatially localized stimuli, mimicking biological morphogenesis and unlocking geometric complexity. This transformation will be enabled by converging technologies [Figure 1B], which depicts the two core components of this paradigm: 4D printing with time-sequenced morphing and artificial intelligence (AI)-assisted manufacturing for ink selection, toolpath optimization, and *in-situ* process monitoring. Among them, 4D printing addresses the geometrical limitations by programming internal stress distributions without support structures. Key examples include biomimetic helical structures for soft grippers[42], kirigami-inspired deployable lattices for adaptive surfaces[43], and tubular constructs for vascular stents[44]. Morphing is triggered by environmental stimuli, including moisture gradients, temperature changes, pH shifts, or ion concentration variations[45].

Resolution and fidelity requirements scale with device size: submillimeter/millimeter-scale for grippers, 0.1 μm - 1 mm for vascular intervention[46,47]. Current DIW achieves 100-1,200 μm[48] and two-photon polymerization achieves sub-micrometer precision[49], yet shape fidelity remains limited by stress relaxation and non-uniform swelling. Critically, stimulus-responsive CP composites have limited actuation frequency, typically 0.1-0.5 Hz[14], slower than dielectric elastomers (400-600 Hz)[50]. Deformation kinetics introduce latency that scales nonlinearly with feature size, rendering thick structures impractical for rapid morphing[51]. A trade-off also exists between structural complexity and mechanical performance: highly porous or thin-walled 4D-printed architectures exhibit reduced load-bearing capacity and compromised fatigue resistance compared to bulk films[52]. Overcoming these limitations requires faster-responding composites, multi-stimuli-responsive material systems, and reinforcement strategies to enhance mechanical robustness without sacrificing morphing capability.

Complementing this, AI-assisted manufacturing employs ML to optimize ink selection, toolpath planning, and real-time monitoring, transforming fabrication into a data-driven, adaptive workflow. This proceeds along three pathways: surrogate modeling using GPR or neural networks to map printing parameters to quality metrics; active learning with BO to identify optimal conditions with minimal iterations; and real-time *in-situ* monitoring with vision-based neural networks for closed-loop defect correction. These approaches expand the manufacturable design space while introducing the intelligence and reproducibility essential for translating CP-based structures to functional robotic systems. Beyond fabrication capability, this paradigm redefines the relationship between design intent and manufacturing reality, liberating roboticists to conceive complex topologies without assembly-based constraints. The design-print-characterize data loop accelerates iteration from conception to realization. Ultimately, this enables not simply more intricate structures, but a fundamental expansion of what is manufacturable and thus achievable in CP-based soft robotics.

## Integrated autonomy system

Sensing, actuation, control, and energy functions should converge within a single CP continuum, moving beyond modular assembly toward fully integrated autonomous systems through material-physical coupling. Achieving this vision requires advances on two fronts [Figure 1C], highlighting the dual pathway of energy-actuation integration and sensing-actuation-control fusion. First, CP supercapacitive properties can enable simultaneous energy storage and actuation, while photothermal or magnetothermal systems provide wireless energy-to-actuation conversion. CP supercapacitors deliver energy densities of ~77.1 $Wh \cdot kg^{-1}$[53], lower than lithium-ion batteries (~350 $Wh \cdot kg^{-1}$)[54], yet combine rapid response with considerable energy storage. Recently, wirelessly rechargeable micro-supercapacitors have been integrated as onboard power sources for untethered soft robots[55], though hybrid architectures remain more practical for sustained operation. The suitability of CPs for embodied computation arises from unique intrinsic properties. Unlike dielectric elastomers requiring kilovolt-level actuation or hydrogels relying solely on slow ionic transport, CPs couple ionic/electronic conduction, meaning mechanical deformation directly alters electronic readout, creating a physical feedback loop for analog computation[56]. Electrochemically driven volume change couples mechanical work with charge state, while strain-induced impedance modulation provides built-in sensing without external transducers. Low-voltage operation (< 1 V), tunable impedance, and intrinsic actuation-sensing coupling, enable CP-based soft robots to collapse sensing, actuation, and processing into a single body.

Second, sensing-actuation-control fusion via PRC uses CP nonlinear dynamics as a computational substrate. PRC has been validated for time-series prediction and pattern classification[57]; an optoelectronic reservoir-computing system achieved handwriting and gesture recognition with > 90% accuracy[58]. Quantitative metrics such as memory capacity provide a rigorous basis for characterizing information processing capability[59]. Compared with conventional controllers, PRC offers higher energy efficiency and lower computational cost, but currently faces challlenges in repeatability, noise, and scaling, motivating hybrid architectures combining physical computing with conventional digital processors[27]. This flattens the sensing, processing, decision, and actuation hierarchy into a direct stimulus-body response mapping, where behavior emerges from material structure rather than external algorithms. The critical barrier is the inherent variability and environmental sensitivity of CP; device-to-device variations and drift under changing temperature and humidity challenge reliability. Emerging mitigation strategies, such as Bayesian uncertainty quantification[60], are being explored to address these reliability challenges. This integration enables truly all-soft, wireless, autonomous CP robotic systems, where functionality emerges from material-physical coupling. This vision demands that functional requirements and material specifications be co-defined by materials scientists and roboticists from the outset, ensuring integration is not an afterthought but an intrinsic feature of the materials themselves.

Beyond embedded computation, AI will serve as a system-level design tool to navigate trade-offs among materials, processing, and applications. Multi-objective optimization and transfer learning can identify Pareto-optimal configurations[61], enabling researchers to answer: which CP formulation, fabrication route, and system architecture best balance performance for a given scenario? Real-world examples validate this: a neuron-inspired control framework integrating meta-learning with online adaptation achieved 44%-55% tracking error reduction and > 92% shape accuracy under varying payloads and actuator failures[62]; active learning enabled automatic strain sensor design from < 0.5% to 350% strain for soft grippers and swimmer robots[63]. These confirm that AI can guide researchers in navigating performance conflicts before physical fabrication.

### Frontier strategic applications

Future developments should establish a closed-loop R&D paradigm linking application scenarios, requirement decomposition, and material inverse design, that anchors CP development and system validation to real-world applications, ensuring materials are developed with clear performance targets. A case study of a CP-based epidermal e-skin interface for upper-limb amputee rehabilitation translates clinical requirements into a multi-material printed system comprising PEDOT:PSS hydrogel, polyvinylidene difluoride (PVDF)/ionic-liquid ink, silver interconnects, and polydimethylsiloxane (PDMS) encapsulation[25]. This closed-loop bidirectional system integrates surface electromyography (sEMG) electrodes and stimulation modules, achieving 98.33% gesture accuracy at 0.1 s latency, shortening the trial-and-error cycle from months to weeks, and providing sEMG sensing via onboard adaptive learning that mitigates motion interference under diverse skin conditions.

Realizing this paradigm demands standardized validation platforms providing reproducible benchmarks for systematic cross-comparison. Community efforts include Design-for-Benchmarking[64] and unified elastomer characterization frameworks[65]. Our proposed application scenario-material performance mapping database complements these by targeting the upstream interface between roboticists and materials scientists. It systematically quantifies application requirements across mechanical, electrical, environmental, and biocompatibility dimensions, creating a continuous pipeline from scenario demands to material delivery and enabling rapid identification of promising candidates before physical prototyping. Interdisciplinary validation standards define service life, environmental tolerance, and functional reliability ratings tailored to healthcare, public safety, deep-sea, and aerospace exploration [Figure 1D], which maps these four frontier domains to their representative application scenarios.

The transformative potential lies in ensuring materials development is never disconnected from applications. For intelligent healthcare, this means autonomic microrobots for vascular intervention and targeted drug delivery leveraging CPs' biocompatibility and biodegradability. For public safety, it enables search-and-rescue systems where acoustic silence and mechanical compliance provide distinct advantages. For deep-sea applications, it exploits resistance to saltwater corrosion, pressure tolerance, and lightweight deployable architectures. For aerospace applications, it leverages radiation resistance and extreme temperature tolerance. Recent demonstrations substantiate these prospects: a soft robotic neuroprosthetic hand for tactile sensation restoration[66]; a vine-like soft robot envisioned for urban search-and-rescue under collapsed structures[67]; an electrohydraulic soft robot deployed at ~4,071 m depth for deep-sea exploration[68]; and soft robots applied to space environments[69]. These applications converge the preceding axes and must be co-developed to deliver system-level functionality beyond laboratory demonstrations toward practical, real-world deployment.

## CONCLUSION

The ultimate promise of CP-based soft robotics lies not in building superior actuators, but in fundamentally reimagining what a robot can be, a paradigm where the material body itself serves as both machine and algorithm. Four interconnected trajectories will shape this transformation: AI-powered autonomous

synthesis that accelerates materials discovery from years to weeks; 4D morphogenesis that enables structures to grow rather than assemble; physical reservoir computing that collapses sensing, actuation, and processing into a single material continuum; and application-driven validation that anchors materials development to real-world performance requirements across healthcare, public safety, deep-sea exploration, and aerospace. Yet critical missing links remain. Current AI approaches are bottlenecked by data infrastructure, as synthesis conditions, processing parameters, and performance data are rarely standardized, machine-readable, or openly shared. Bridging this gap will require community-wide data standards and closed-loop platforms where AI-guided synthesis is validated by automated experimentation. Addressing these gaps will determine whether CP-based soft robotics remains a laboratory curiosity or becomes a cornerstone of embodied intelligence. The physical laws of CPs are themselves the algorithm, not encoded, but embodied.

## DECLARATIONS

### Authors' contributions

Writing - original draft: Yao, M.
Literature review, writing - review and editing: Yao, M.; Li, G.; Zhang, L.; Jiang, Q.; Ma, Y.; Lu, B.
Conceptualization, supervision: Jiang, Q.; Ma, Y.; Lu, B.

### Availability of data and materials

Not applicable.

### AI and AI-assisted tools statement

During the preparation of this Perspective article, the authors used DeepSeek (version V4, released 2026-04-24) to assist with English language editing, grammatical correction, and improving the clarity and readability of the text. Additionally, Nano Banana (version 2.0, released 2026-02-26) was used as an auxiliary rendering aid for certain visual refinements in Figure 1, while all elements, shapes, colors, and layouts were manually designed and drawn by the authors from scratch using Adobe Illustrator. These tools were not used to generate scholarly arguments, develop the conceptual framework, or draw the conclusions of the article. All AI-assisted outputs were carefully reviewed, edited, and verified by the authors, who take full responsibility for the accuracy, originality, and integrity of the final manuscript.

### Financial support and sponsorship

This work was supported by the National Natural Science Foundation of China (52473179, 52673229, 22575091, and 92463310), the "Climbing Project" of Helanshan Laboratory (HLS-2026-PDJH-025), and the Jiangxi Provincial Key Laboratory of Flexible Electronics (20242BCC32010).

### Conflicts of interest

All authors declared that there are no conflicts of interest.

### Ethical approval and consent to participate

Not applicable.

### Consent for publication

Not applicable.

### Copyright

© The Author(s) 2026.

## REFERENCES

1. Wang, X.; Wei, R.; Chen, Z.; et al. Bioinspired intelligent soft robotics: from multidisciplinary integration to next-generation intelligence. *Adv. Sci.* **2025**, *12*, e06296. DOI PubMed PMC
2. Wang, D.; Zhao, B.; Li, X.; et al. Dexterous electrical-driven soft robots with reconfigurable chiral-lattice foot design. *Nat. Commun.* **2023**, *14*, 5067. DOI PubMed PMC
3. Li, J.; Cao, J.; Lu, B.; Gu, G. 3D-printed PEDOT:PSS for soft robotics. *Nat. Rev. Mater.* **2023**, *8*, 604-22. DOI

4. Kulkarni, M.; Edward, S.; Golecki, T.; Kaehr, B.; Golecki, H. Soft robots built for extreme environments. *Soft Sci.* **2025**, *5*, 12. DOI
5. Zhang, Z.; Chen, G.; Xue, Y.; et al. Fatigue-resistant conducting polymer hydrogels as strain sensor for underwater robotics. *Adv. Funct. Mater.* **2023**, *33*, 2305705. DOI
6. Li, Y.; Gao, Y.; Lan, L.; et al. Ultrastretchable and wearable conductive multifilament enabled by buckled polypyrrole structure in parallel. *npj Flex. Electron.* **2022**, *6*, 42. DOI
7. Yu, X.; Zhang, H.; Wang, Y.; et al. Highly stretchable, ultra-soft, and fast self-healable conductive hydrogels based on polyaniline nanoparticles for sensitive flexible sensors. *Adv. Funct. Mater.* **2022**, *32*, 2204366. DOI
8. Shen, Z.; Zhang, Z.; Zhang, N.; et al. High-stretchability, ultralow-hysteresis conducting polymer hydrogel strain sensors for soft machines. *Adv. Mater.* **2022**, *34*, e2203650. DOI PubMed
9. Hu, F.; Xue, Y.; Xu, J.; Lu, B. PEDOT-based conducting polymer actuators. *Front. Robot. AI* **2019**, *6*, 114. DOI PubMed PMC
10. Sarker, A.; Ul Islam, T.; Islam, M. R. A review on recent trends of bioinspired soft robotics: actuators, control methods, materials selection, sensors, challenges, and future prospects. *Adv. Intell. Syst.* **2025**, *7*, 2400414. DOI
11. Tazwar, H. T.; Antora, M. F.; Nowroj, I.; Rashid, A. B. Conductive polymer composites in soft robotics, flexible sensors and energy storage: fabrication, applications and challenges. *Biosens. Bioelectron. X* **2025**, *24*, 100597. DOI
12. Chen, G.; Zhang, Y.; Li, S.; et al. Flexible artificial tactility with excellent robustness and temperature tolerance based on organohydrogel sensor array for robot motion detection and object shape recognition. *Adv. Mater.* **2024**, *36*, 2408193. DOI PubMed
13. Weng, M.; Zhou, J.; Zhou, P.; et al. Multi-functional actuators made with biomass-based graphene-polymer films for intelligent gesture recognition and multi-mode self-powered sensing. *Adv. Sci.* **2024**, *11*, 2309846. DOI PubMed PMC
14. Gao, R.; Chen, W.; Zhang, X.; Chen, X.; Lu, C. Sensing-actuation system with zero signal delay for ultrasensitive recognition. *Mater. Today* **2025**, *88*, 338-47. DOI
15. Pai, S. M.; Shah, K. A.; Sunder, S.; Albuquerque, R. Q.; Brütting, C.; Ruckdäschel, H. Machine learning applied to the design and optimization of polymeric materials: a review. *Next Mater.* **2025**, *7*, 100449. DOI
16. Cheng, M.; Fu, C. L.; Okabe, R.; et al. Artificial intelligence-driven approaches for materials design and discovery. *Nat. Mater.* **2026**, *25*, 174-90. DOI
17. Chen, Z.; Liu, K.; Zhou, J.; et al. Channel confinement: a novel approach to tackle batch variation in conjugated polymers for organic electrochemical transistors. *Adv. Mater.* **2026**, *38*, e10659. DOI PubMed
18. Wang, J.; Sun, Y.; Chen, Q.; et al. OpenPoly: a polymer database empowering benchmarking and multi-property predictions. *Chin. J. Polym. Sci.* **2025**, *43*, 1749-60. DOI
19. Nardes, A.; Kemerink, M.; Janssen, R.; et al. Microscopic understanding of the anisotropic conductivity of PEDOT:PSS thin films. *Adv. Mater.* **2007**, *19*, 1196-200. DOI
20. Li, J.; Cao, J.; Bian, R.; et al. Multimaterial cryogenic printing of three-dimensional soft hydrogel machines. *Nat. Commun.* **2025**, *16*, 185. DOI PubMed PMC
21. Tian, Y.; Li, Y. T.; Tian, H.; Yang, Y.; Ren, T. L. Recent progress of soft electrothermal actuators. *Soft Robot.* **2021**, *8*, 241-50. DOI
22. Plateau, T. P.; Pham, H.; Park, J. Atomized oxidative polymerization as a 3D printing platform for binder-free, bulk conductive polymer architectures. *Adv. Funct. Mater.* **2026**, *36*, e76488. DOI
23. Liu, Y.; Wang, X.; Wang, J.; et al. Bioinspired structural design enables synergistic toughness and conductivity in hydrogels for advanced wearable electronics. *Nano-Micro Lett.* **2026**, *18*, 249. DOI PubMed PMC
24. Ma, T.; Zhang, Y.; Ruan, K.; et al. Advances in 3D printing for polymer composites: a review. *InfoMat* **2024**, *6*, e12568. DOI
25. Wang, G.; Tang, Y.; Luo, X.; et al. Printed sensing human-machine interface with individualized adaptive machine learning. *Sci. Adv.* **2025**, *11*, eadw3725. DOI PubMed PMC
26. Hu, H.; Zhang, S.; Zhang, M.; et al. Artificial muscles based on coiled conductive polymer yarns. *Adv. Funct. Mater.* **2024**, *34*, 2401685. DOI
27. Wang, J.; Zhou, Z.; Kahak, A.; Li, S. Embodying physical computing into soft robots. *Nat. Commun.* **2026**, *17*, 2455. DOI PubMed PMC
28. Li, X.; Xu, R.; Xie, C.; Ge, Z.; Gao, B.; Lim, C. T. Microscale architectures for intelligent soft robotics: from functional microneedles to biointegrated wearable systems. *Nano-Micro Lett.* **2026**, *18*, 179. DOI PubMed PMC
29. Li, Z.; Tang, H.; Liang, Y.; et al. Practical lithium-organic batteries enabled by an n-type conducting polymer. *Nature* **2026**, *651*, 100-6. DOI PubMed
30. Liu, Q.; Zheng, Y.; Wu, H.; et al. Intrinsically stretchable complementary circuits based on direct photo-patternable polymer semiconductors. *Nat. Electron.* **2026**, *9*, 507-18. DOI
31. Wu, X.; Xu, P.; Zhang, Z.; et al. Ultrasoft iontronics: stretchable diodes enabled by ionically conductive bottlebrush elastomers. *Adv. Funct. Mater.* **2025**, *35*, 2503859. DOI
32. Lin, D. Z.; Pan, K. J.; Li, Y.; et al. A high-throughput experimentation platform for data-driven discovery in electrochemistry. *Sci. Adv.* **2025**, *11*, eadu4391. DOI PubMed PMC

33. Jang, H.; Lee, W.; Kim, H. J.; et al. Active learning-guided accelerated discovery of ultra-efficient high-entropy thermoelectrics. *Adv. Mater.* **2026**, *38*, e15054. DOI
34. Zhang, Y.; Xu, X. Machine learning glass transition temperature of polyacrylamides using quantum chemical descriptors. *Polym. Chem.* **2021**, *12*, 843-51. DOI
35. Medina, H.; Drake, R. Graph neural networks for polymer characterization and property prediction: opportunities and challenges. *J. Chem. Inf. Model.* **2026**, *66*, 1316-36. DOI PubMed PMC
36. Asare, E. A.; Abdul-Wahab, D.; Kaufmann, E. E.; Wahi, R.; Ngaini, Z. Interpretable multi-objective machine learning with calibrated uncertainty for deployment-oriented prediction of defects and properties in polymer FFF. *Measurement* **2026**, *258*, 119350. DOI
37. Agarwal, M.; Pasupathy, P.; Wu, X.; Recchia, S. S.; Pelegri, A. A. Multiscale computational and artificial intelligence models of linear and nonlinear composites: a review. *Small Sci.* **2024**, *4*, 2300185. DOI PubMed PMC
38. Gao, L.; Song, S.; Lin, J.; Xu, Y.; Wang, L.; Du, L. AI-assisted design of advanced polymeric materials: challenges and solutions. *Adv. Mater.* **2026**, *38*, e16857. DOI PubMed
39. Martin, T. B.; Audus, D. J. Emerging trends in machine learning: a polymer perspective. *ACS Polym. Au* **2023**, *3*, 239-58. DOI PubMed PMC
40. Fang, Y.; Jin, Y.; Gao, H. A unified kinetic Monte Carlo and Bayesian optimization framework for the circular design of poly(methyl methacrylate): from synthesis to recycling. *Chem. Eng. J.* **2026**, *538*, 176625. DOI
41. Vogel, G.; Weber, J. M. Inverse design of copolymers including stoichiometry and chain architecture. *Chem. Sci.* **2025**, *16*, 1161-78. DOI PubMed PMC
42. Song, J.; Feng, Y.; Hong, Z.; et al. Octopus-inspired adaptable soft grippers based on 4D printing: numerical modeling, inverse design, and experimental validation. *Adv. Intell. Syst.* **2023**, *5*, 2200384. DOI
43. Zhao, Z.; Cao, X.; Duan, S.; et al. 4D-printed “Ori-Lattice” with ultrahigh foldability and load-bearing capacity. *Adv. Funct. Mater.* **2026**, *36*, e24106. DOI
44. Li, Y.; Pan, Y.; Imashiro, C.; et al. Adaptive 4D-printed vascular stents with low-temperature-activated and intelligent deployment. *Adv. Funct. Mater.* **2026**, *36*, e21468. DOI
45. Ren, Z.; Fan, X.; Xie, H.; Sun, M. 4D-printed soft microrobots: manufacturing, materials, actuation and applications. *Soft Sci.* **2026**, *6*, 6. DOI
46. Yang, Y.; Shi, W.; Yang, B.; Xiong, T.; Li, Z. A.; Ren, H. Regrafting submillimeter-scale ferromagnetic soft continuums. *Nat. Commun.* **2025**, *16*, 7023. DOI PubMed PMC
47. Ji, X. Y.; Zhu, J. Q.; Wu, K.; et al. Soft robotic devices for cardiovascular medicine. *Nat. Rev. Cardiol.* **2026**, *23*, 769-87. DOI
48. Sol, J. A. H. P.; Smits, L. G.; Schenning, A. P. H. J.; Debije, M. G. Direct ink writing of 4D structural colors. *Adv. Funct. Mater.* **2022**, *32*, 2201766. DOI
49. Ren, Z.; Xin, C.; Liang, K.; et al. Femtosecond laser writing of ant-inspired reconfigurable microbot collectives. *Nat. Commun.* **2024**, *15*, 7253. DOI PubMed PMC
50. Ji, X.; Liu, X.; Cacucciolo, V.; et al. An autonomous untethered fast soft robotic insect driven by low-voltage dielectric elastomer actuators. *Sci. Robot.* **2019**, *4*, eaaz6451. DOI
51. Ni, C.; Chen, D.; Yin, Y.; et al. Shape memory polymer with programmable recovery onset. *Nature* **2023**, *622*, 748-53. DOI
52. Morales Ferrer, J. M.; Kekedjian, C.; Bacca, N.; Boley, J. W. Synthetic fascia for stiff and tough 4D printed multifunctional structures that detect and tolerate damage. *Nat. Commun.* **2025**, *16*, 10351. DOI PubMed PMC
53. Abdelnaser, S.; Kuo, S.; El-Mahdy, A. F. Conjugated microporous polymers incorporating pyridine moieties for efficient faradaic supercapacitor energy storage. *J. Power Sources* **2025**, *635*, 236535. DOI
54. Xu, C.; Peng, B.; Yang, W.; Tian, J.; Zhou, H. High energy density lithium battery systems: from key cathode materials to pouch cell design. *Chem. Soc. Rev.* **2025**, *54*, 10245-303. DOI
55. Nardekar, S. S.; Kim, S. J. Untethered magnetic soft robot with ultra-flexible wirelessly rechargeable micro-supercapacitor as an onboard power source. *Adv. Sci.* **2023**, *10*, 2303918. DOI PubMed PMC
56. Krauhausen, I.; Coen, C.; Spolaor, S.; Gkoupidenis, P.; van de Burgt, Y. Brain-inspired organic electronics: merging neuromorphic computing and bioelectronics using conductive polymers. *Adv. Funct. Mater.* **2024**, *34*, 2307729. DOI
57. Han, C.; Kim, M.; Park, S. J.; et al. Reconfigurable organic electrochemical transistors with high dynamic ranges for fully integrated physical reservoir computing. *Adv. Funct. Mater.* **2025**, *35*, 2423814. DOI
58. Wu, X.; Wang, S.; Huang, W.; Dong, Y.; Wang, Z.; Huang, W. Wearable in-sensor reservoir computing using optoelectronic polymers with through-space charge-transport characteristics for multi-task learning. *Nat. Commun.* **2023**, *14*, 468. DOI PubMed PMC
59. Usami, Y.; van de Ven, B.; Mathew, D. G.; et al. In-materio reservoir computing in a sulfonated polyaniline network. *Adv. Mater.* **2021**, *33*, 2102688. DOI PubMed PMC

60. Wang, E.; Lei, Z.; Wen, G.; et al. A physics-constrained Bayesian neural network for machinery remaining useful life prediction and uncertainty quantification. *Reliab. Eng. Syst. Saf.* **2026**, *266*, 111778. DOI
61. Cao, Q.; Liu, S.; Varghese, A. J.; Darbon, J.; Triantafyllou, M. S.; Karniadakis, G. E. Automatic selection of the best neural architecture for time series forecasting. *Nat. Commun.* **2026**, *17*, 7058. DOI PubMed PMC
62. Tang, Z.; Tian, L.; Xin, W.; Wang, Q.; Rus, D.; Laschi, C. A general soft robotic controller inspired by neuronal structural and plastic synapses that adapts to diverse arms, tasks, and perturbations. *Sci. Adv.* **2026**, *12*, eaea3712. DOI PubMed PMC
63. Yang, H.; Li, J.; Lim, K. Z.; et al. Automatic strain sensor design via active learning and data augmentation for soft machines. *Nat. Mach. Intell.* **2022**, *4*, 84-94. DOI
64. Lo Preti, M.; Nazeer, M. S.; Pinskier, J.; Howard, D.; Laschi, C. Design-for-benchmarking in soft robotics: navigating component-system dichotomy. *Adv. Intell. Syst.* **2026**, *8*, e202600002. DOI
65. Roels, E.; Costa Cornellà, A.; Brancart, J. A standardized framework for elastomer characterization in soft robotics. *Adv. Intell. Syst.* **2026**, *8*, e202500699. DOI
66. Xu, H.; Chai, G.; Zhang, N.; Gu, G. Restoring finger-specific tactile sensations with a sensory soft neuroprosthetic hand through electrotactile stimulation. *Soft Sci.* **2022**, *2*, 19. DOI
67. Godoy, S. L.; McFarland, C.; Val, M.; Valdivia, A. A.; Hanson, N.; McGuinness, M. Distributed acoustic localization array deployed using a soft everting vine robot. *arXiv* **2026**, arXiv:2607.20392. Available online: https://doi.org/10.48550/arXiv.2607.20392. (accessed 2026-11-04).
68. Li, G.; Shen, P.; Wong, T. W.; et al. Plasticized electrohydraulic robot autopilots in the deep sea. *Sci. Robot.* **2025**, *10*, eadt8054. DOI
69. Zhang, Y.; Li, P.; Quan, J.; Li, L.; Zhang, G.; Zhou, D. Progress, challenges, and prospects of soft robotics for space applications. *Adv. Intell. Syst.* **2023**, *5*, 2200071. DOI


**Disclaimer/Publisher's Note:** All statements, opinions, and data contained in this publication are solely those of the individual author(s) and contributor(s) and do not necessarily reflect those of OAE and/or the editor(s). OAE and/or the editor(s) disclaim any responsibility for harm to persons or property resulting from the use of any ideas, methods, instructions, or products mentioned in the content.

© The Author(s) 2026. Open Access This article is licensed under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, sharing, adaptation, distribution and reproduction in any medium or format, for any purpose, even commercially, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.