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MODERN APPROACHES TO MANUFACTURING AND REGULATING IONIC POLYMER-METAL COMPOSITES: A REVIEW

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Abstract: This study offers a thorough overview and introduction to smart materials, emphasising ionic polymers, particularly ionic polymer-metal composites (IPMCs). These materials have lightweight, adaptability, and low power requirements, which have contributed to their being more well-known for their potential in biomedical devices, soft robotics, and micro/nano systems. This overview highlights significant advancements in fabrication methods, material composition, and performance benefits. It focuses attention on new developments such as enhanced polymer matrices, layered structural designs, and the application of advanced electrode materials. Applications in bio-inspired robotics, artificial muscles, and sensor systems are investigated. The investigation also looks at more recent developments that provide better functionality in IPMCs. Even with major advancements, maintaining stability and reliable performance over a prolonged period remains difficult. More extensive integration into smart systems and affordable production techniques are anticipated to be the main topics of future study. Along with emphasizing current research demands, this review offers a comparative analysis of current fabrication and performance improvement techniques. It aims to provide a framework of reference for upcoming advancements in high-performance smart systems based on IPMC.
Key words: ionic polymer metal composite (IPMCs), smart material, preparation process, application, model, and future challenges.

1. INTRODUCTION

In recent decades, IPMCs have acquired recognition as being among of the most attractive smart materials because of their distinctive electromechanical capabilities and wide range of uses in sensors, medical devices, soft automation, and regulators. When exposed to an electric field, a new class of flexible functional materials, identified as electroactive polymers, can produce various mechanical movements and after removing the external electric field, they restore to their initial shape, [1]. A compact design, exceptional flexibility, great fracture resistance, and simplicity of shape and modeling are only some of the advantages associated with electroactive polymers, [2]. When the material is subjected to an electromagnetic field under mechanical stress, the ions inside it rearrange internally, giving rise to these features. These materials fundamentally act as Smart material response transducers, [88]. Ionic Electroactive Polymer-based, actuators have many benefits, such as versatility, low weight, significant deformation capability, low operating voltage, biocompatibility, a high force-to-weight ratio, and the capacity to operate in both open air and aquatic conditions, [3]. It is possible to produce these materials in a wide range of forms and at minuscule sizes. Because of these features, Ionic Electroactive Polymer based actuators have a lot of potential for application in soft robotics applications. Some of the materials used in Ionic Electroactive Polymer are also recyclable and regarded as reasonably safe for use in healthcare fields, [4]. Consequently, they are viewed as feasible options for high-precision medical devices, such as flexible, soft needles with built-in actuation systems, [89].
In 1992, Shahinpoor and his colleagues first introduced Ionic Polymer-Metal Composites (IPMCs), which were eventually used in swimming robots, among numerous other applications, [5].
Finite element and theoretical models were created by Segalman and others to explain their electro-chemo-mechanical function. The effects of internal electromagnetic fields, ion transport, and solvent diffusion on polymer deformation were taken into account in these models, [6]. The roles of cation types and cluster configurations, sensing, and actuation were all influenced by researchers such as Nemat-Nasser and Weiland. Based on the

material and cations employed in the membrane, IPMCs usually bend towards the anode when exposed to voltage before gradually relaxing, according to investigations, [7].
IPMCs are primarily restricted to research because of their weak sensing currents, poor actuation force, and non-linear nature, [8]. Their transduction effectiveness is highly influenced by the characteristics of the electrode, intermediate layers, and polymer. To improve their performance and practicality, research is always being conducted to improve manufacturing, description, modelling, and management, [9]. IPMCs research has recently advanced with a focus on improving effectiveness, environmental versatility, and practicality, including multilayer structures and operating under severe temperatures, [90]. Furthermore, because of their low hydrodynamic impacts, they have been shown to offer potential in energy gathering, saltwater operation, and simplified modelling. In addition to actuation, IPMCs exhibit promise in mechanoelectrical sensing through the generation of energy under bending or pressure, which allows them to be used as biomimetic and sensitive vibration sensors, [10]. Although notable progress in IPMC research, there is still a dearth of comprehensive and integrated reviews that concurrently address performance improvement techniques, sophisticated multidimensional modeling techniques, and new soft robotic and biomedical applications, [91]. There is a gap in unified analysis because the majority of current studies examine these topics separately. To speed up translational development, a methodical assessment that links material design, modeling approaches, and real-world application is necessary.
This paper presents a complete analysis of IPMC flexible actuators, concentrating on performance enhancements, modeling methodologies, and different applications in robotics, opto-mechatronics, and medical engineering. It also describes current progress, potential research directions, and difficulties to guide ongoing development in the area of inquiry.

2. OVERVIEW ON PROGRESS IN PERFORMANCE OPTIMIZATION OF IPMCS

The IPMC performance optimization efforts primarily focus on enhancing the mechanical efficiency, robustness, and response of these devices, [11]. To increase their overall functionality, researchers have looked into better hydration methods, sophisticated electrode structures, and material improvements. These advancements are aimed at expanding the possible applications of IPMC in medical devices, artificial muscles, and soft robotics technologies, [12]. IPMCs exhibit significant potential because of their lightweight structure, high flexibility, and low-voltage operation, which is compatible with the increasing need for tiny and flexible actuators and sensors brought about by the development of soft robotics. Smart sensing systems, biomedical equipment, and underwater robotics are just a few of the sectors in which they have found use. The constraints, including decreased force production, instability at constant voltage, and solvent loss, continue, though, and motivate scientists to advance manufacturing processes and materials, [13]. Due to their short air lifetime and low output force, IPMCs have limited practical use, so researchers are looking for ways to improve both. The performance of IPMCs is affected by a number of factors, including membrane thickness, electrode structure, ion concentration, and water content, [14]. One of the main areas of focus is improving this compound matrix, which has a direct impact on conductivity, elasticity, capacitance, and ion migration. Attempts to improve the Nafion matrix by altering the barrier thickness or adding nanoparticles have demonstrated improvements in strength, conductivity, and overall functionality of multi-walled carbon nanotubes (MWCNTs), which have proven particularly effective among these because of their superior dispersibility and electrical properties. IPMC Nafion matrix is a sulfonated tetrafluoroethylene-based fluoropolymer composed of hydrophilic sulfonate ($–SO_3^-$) ionic groups that facilitate ion migration and a chemically stable hydrophobic backbone. For actuation and energy transmission, these ionic domains allow the movement of exchanged cations (like Li^+) or charge carriers like H^+. Its toughness, ionic conductivity, and overall actuation performance can all be enhanced by ion-exchange implantation, additive addition, and molding methods, including hot pressing or casting. With the goal to improve ionic conductivity, stiffness, solvent retention, and overall actuation performance, recent manufacturing and regulation strategies optimize ion-exchange doping, incorporate nanofillers, and apply new fabrication techniques to the Nafion matrix in IPMCs. Although carbon nanomaterial-enhanced polymer composites are employed in many technical domains, their natural tendency to aggregate may reduce their efficacy.
Without causing structural damage, methods such as surface modification, chemical treatment, and ultrasonication enhance dispersion and integration, improving IPMCs' electrical and mechanical performance.
The primary traits, process adjustments, performance indicators, and related regulatory and quality control requirements of modern production and optimization techniques for IPMCs are outlined in Table 1. It integrates each method to industry standards, safety, and compliance while highlighting a variety of technological advancements, such as 3D printing and fabrication aided by nanoparticles.

Table 1. An overview of Ionic Polymer–Metal Composites (IPMCs): Current Manufacturing Methods, Improvement Approaches, and Regulatory Implications

Ref.	Manufacturing Approach	Key Features / Advantages	Methods Changes	Metrics Improved	Regulatory/Quality Considerations
[15]	Electroless Plating for IPMCs	Uniform electrode deposition, cost-effective	Chemical reduction on Nafion-based membranes	Conductivity, adhesion	REACH/RoHS compliance; chemical waste management
[16]	Electroplating Enhancementfor IPMCs	Higherdurability and conductivity	Secondary metal deposition after seeding	Surface resistance, tensile strength	Wastewater treatment; electrode uniformity testing
[17]	Layer-by-Layer (LbL) IPMC Assembly	Nano scale precision	Alternating polyelectrolyte/metal deposition	Actuation Precisions sensitivity	ISO 13485 documentation for biomedical devices
[18]	Nanoparticle-AssistedIPMC Fabrication	Enhanced surface area, lower voltage operation	NP doping into the polymer matrix or electrode	Actuation force, response time	Nanoparticle release safety; toxicity standards
[19]	3D Printing of IPMCs with Conductive Inks	Rapid prototyping, complex shapes	Additive manufacturing using polymer–metal inks	Customgeometry performance	Additive manufacturing qualification; biocompatibility
[20]	Hybrid Chemical–Mechanical Processing of IPMCs	Structuralrobustness	Precision machining + chemical plating	Stability, bending endurance	Multi-step process traceability; operator safety
[21]	Ionic Liquid Doping in IPMCs	Long-term hydration stability	Nafion + ionic liquid blending	Displacement stability in air	Regulatory clearance for ionic liquids in devices
[22]	Plasma Surface Treatment of IPMCs	Improved electrode–polymer adhesion	Plasma etching prior to plating	Interface bonding, displacement	Emission control for plasma systems
[23]	Carbon Nanotube (CNT) Electrode IPMCs	Lightweight,high conductivity	CNT layer coating instead of metals	Flexibility, conductivity	Nanocarbon safety proto-cols
[24]	Graphene-EnhancedIPMC Electrodes	High electrochemical area	Spray/inkjet graphene on polymer	Force output, voltage efficiency	Nanomaterial-specific regulations
[25]	PEDOT: PSS Conductive Polymer IPMCs	Flexible,corrosion-resistant	Electrode replacement with conductive polymer	Durability, low-voltage actuation	Medical-grade polymer certification
[26]	Hot-Press Lamination for IPMCs	Improvedelectrode integration	Heatand pressure bonding	Mechanical strength, sealing	Thermal process safety
[27]	Micro needle Roller Surface Roughening	Larger effective contact area	Mechanicalrolling before plating	Displacement, blocking force	Tool safety and operator protection
[28]	Multi-Layer Stacking IPMCs	Higher blocking force	Stacked membrane fabrication	Force output	ISO design verification for multi-layer actuators
[29]	Pt Dispersion Optimization in IPMCs	Low-voltage,high-performance	Uniform Pt nano particle distribution	Voltage efficiency	Platinum waste recovery

[30]	Composite Membrane IPMCs	Custom mechanical properties	Nafion blends with PEO, PVDF, etc.	Force/displacement trade-off tuning	Biocompatibility and cytotoxicity testing
[31]	Solvent-Cast IPMC Membranes	Low-costscalable membranes	Solvent evaporation casting	Uniformity, repeatability	VOC emission standards
[32]	AI-Optimized NP IPMC Design	Data-driven material tuning	ML algorithms for NP/electrode choice	Multimetric performance	Data integrity compliance
[33]	Electrode Penetration Control in IPMCs	Balanced flexibility/conductivity	Time-controlled plating	Mechanical flexibility, conductivity	QC for electrode depth uniformity
[34]	Bio-Inspired IPMC Structures	Biomimetic actuation	Patterned electrodes	Natural motion replication	Ethical review for biomedical robotics

3. IPMCS MANUFACTURING PROCEDURE

Ionic Polymer-Metal Composites (IPMCs) are often produced through electrodeposition of precious metals like platinum or gold onto Nafion membranes to form conductive electrodes, [35]. To improve actuation performance, durability, and ionic conductivity, some treatments are being refined, such as surface roughening, ion exchange treatments, and deposition processes. There are five essential processes in the fabrication of IPMCs, starting with the selection of raw materials and ending with post-treatment [36]. Since a polymer membrane layered with electrodes is essential to their operation and ion movement under voltage permits actuation, research focuses on enhancing base film production and electrode plating to improve uniformity, conductivity, and overall performance, [37].

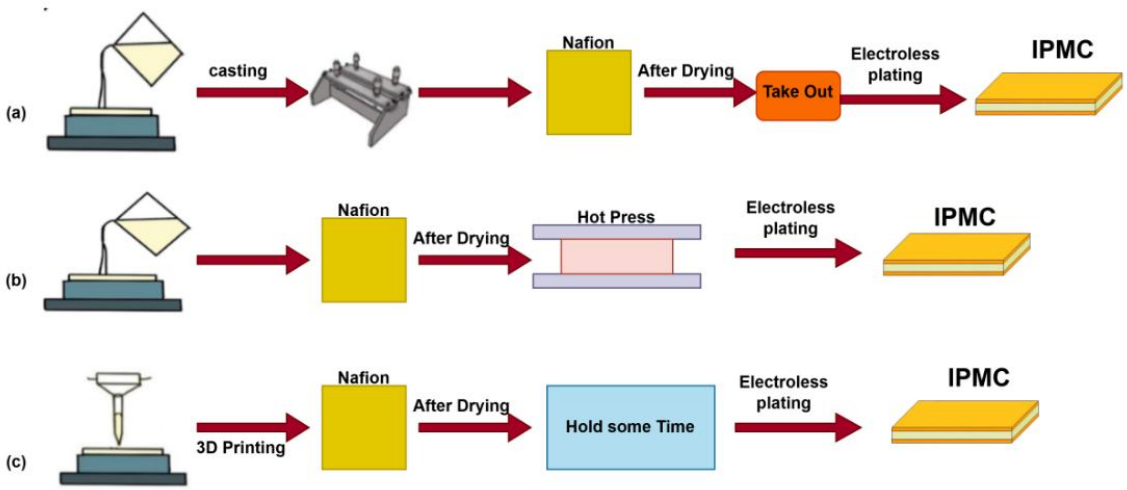

Fig. 1. IPMC fabrication techniques shown vertically: (a) solution casting, (b) hot pressing, and (c) Nafion 3D printing

IPMCs can use various methods for their base membranes, including solution casting, hot pressing, and even 3D printing, [38]. Solution casting offers advantages and disadvantages like any other technique. In this technique, a film is made by pouring a resin solution on a surface, and after some time, during which the appropriate solvent is used, a thin, uniform film is obtained. Unlike this method, hot pressing is quick, although it is costly, [39]. Here, several polymer layers are fused into a single film, which requires great heat and pressure. While 3D printing can take a long time and be expensive, it offers a great advantage in its material efficiency, allowing for greater complexity in the shape of the IPMCs. While the chemical plating method is limited in its ability to control thickness, it is fast and common, which works in its favor for plating electrodes. Sputtering deposition and electroplating have their advantages and disadvantages, too, [40]. While sputtering provides smooth, uniform coatings, it requires a vacuum system, which can be limiting. On the other hand, electroplating boosts conductivity and durability, but is costly and energy inefficient. Direct plating has its problems, too, but requires great expertise. By layering the polymers and electrodes on a metal foil, fast and low-cost options are made possible, [41].
To improve IPMC's functions for varying devices, it is common for researchers to combine several methods, as it allows for the removal of restrictions placed on individual techniques by trading off their unique advantages.

Figure 1 shows three methods for the fabrication of IPMC (Ionic Polymer-Metal Composite) materials: (a) solution casting, (b) hot pressing, and (c) 3D printing. For all fabrication methods, a Nafion precursor is prepared and dried before electroless plating is performed to yield the final IPMC device.
The advantages and disadvantages of different IPMC fabrication techniques will be compared in Figure 2. Although solution casting is easy to control and provides uniform thickness, its use is restricted by solvent compatibility and an extensive preparation period, [42]. Despite requiring costly equipment, hot pressing is effective and produces films rapidly. Elaborate layouts and outstanding resource utilization are made possible by 3D printing; however, it has drawbacks such as high costs, slow speed, and poor precision. Chemical plating has a wide range of deposition capabilities and is quick and affordable, but it lacks precise control over film quality, [43].

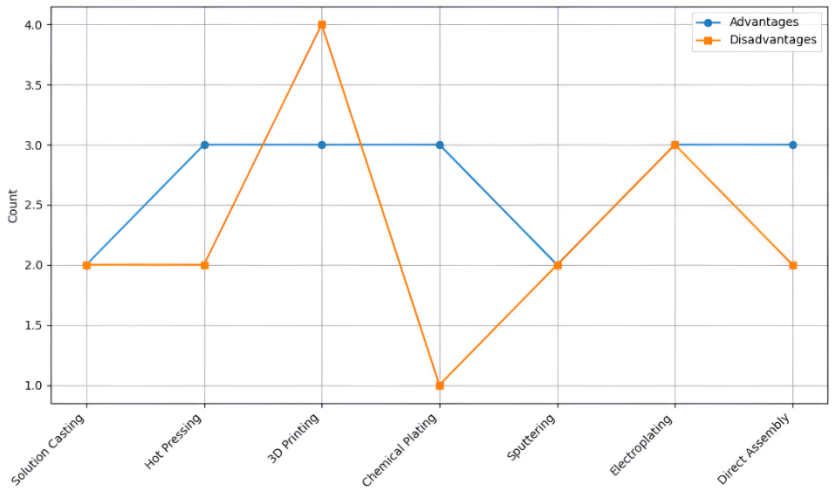

Fig. 2. Advantages and disadvantages of different IPMC fabrication techniques

The phenomenon deposition produces consistent, high-quality films, but it requires specialized, expensive equipment and vacuum conditions, [44]. Electroplating increases conductivity and structural strength, but it requires a lot of energy, is expensive, and has a significant risk of imperfections. Direct assembly is low-cost and environmentally beneficial, but it necessitates technical skill and meticulous process management. Overall, the graph demonstrates a trade-off between performance and usability among different strategies.

4. WORKING PRINCIPLE OF IPMC-BASED SMART MATERIALS

Ion migration within a polymer membrane in response to an electric field is the basis for the workings of IPMC-based smart materials, [45]. In a variety of usage, this movement allows the material to function as an actuator or sensor by causing bending or deformation.

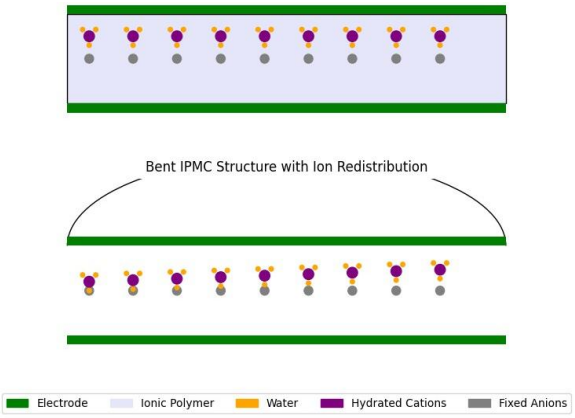

Fig. 3. A demonstration of ion redistribution for sensing and actuation applications using an ionic polymer-metal composite (IPMC) in both straight and bending circumstances

A central ionic membrane, such as Nation, is usually positioned between two noble metal electrodes, such as platinum or gold, in IPMC. Cations and water molecules move towards the cathode when an electric field is

applied, resulting in bending because of the uneven distribution of ions, [46]. On the other hand, IPMC functions as both an actuator and a sensor when mechanical deformation causes ion migration, which produces a voltage, [47]. Figure 3 demonstrates the way an Ionic Polymer-Metal Composite (IPMC) responds when it is bent and when it is not. While fixed anions stay immobile under bending deformation, hydrated cations redistribute towards the stretched (outside) side. Because of the internal electric field produced by this ion migration, the IPMC can act as a soft sensor and actuator.

5. SMART OPTIMIZATION APPROACHES FOR IPMC-BASED ACTUATORS

Optimization of design parameters and operating scenarios to increase IPMC-Based Actuators' efficiency, flexibility, and durability is the primary purpose of smart optimization approaches, [48]. These methods help to improve performance with reduced energy consumption and precise motion control. The actuators are capable of exceeding the specifications of certain systems by deliberately improving their design features and the characteristics of the materials, [49]. In robotics, IPMCs, also known as "artificial muscles". It is frequently employed as an actuator in robotic animals and mobile devices, simulating the behaviours of actual muscles. Innovations such as multilegged robots, lens actuators, tiny pumps, and dust removers for space cameras have been powered by them, [50].

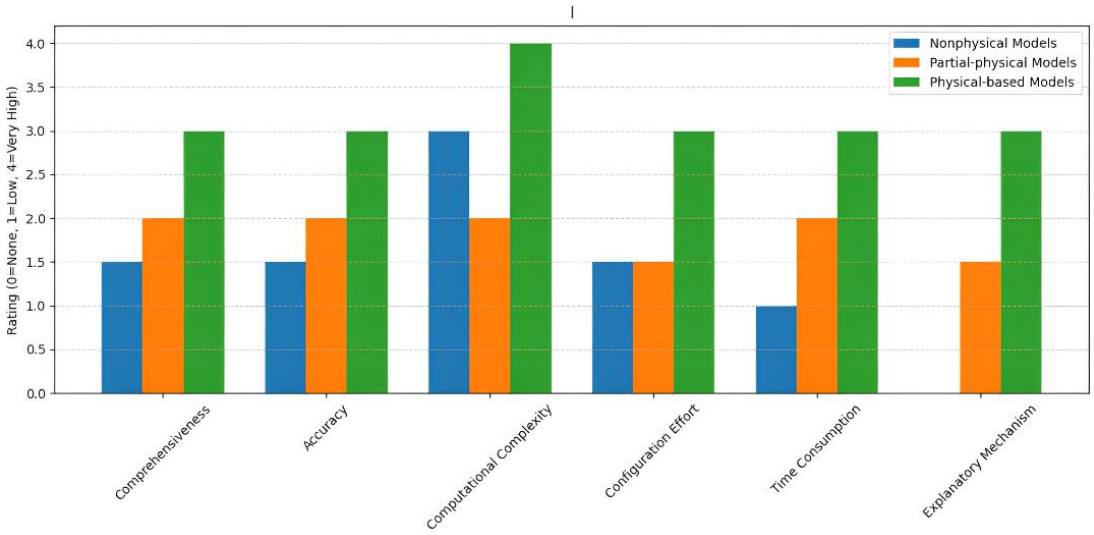

Fig. 4. IPMC Actuator Load comparison

Figure 4 compares three different IPMC actuator model types based on six important performance parameters. Nonphysical models provide simplicity but have lesser accuracy and explanatory power than physical-based models, which rank highest in comprehensiveness, accuracy, and mechanism description, [51].
The ionomer and metal electrodes of IPMCs have a crucial interfacial layer that greatly affects their actuation performance, mostly because of susceptibility. Gold, palladium, or platinum-based dendritic interfacial electrodes (DIEs) have a greater surface area than granular ones, which improves electromechanical efficiency. IPMC's effectiveness in soft robotics scenarios is significantly increased by the formation of these high-surface-area DIEs by techniques like as electroplating and impregnationreduction, [52]. Self-sensing actuation tackles improve integration and eliminate the need for extra sensors by enabling simultaneous sensing and actuation within a single smart material, [53]. Carbon nanofibers, dielectric elastomers, magnetorheological elastomers, and piezoelectric are among the materials on which these techniques have been applied. They have a wide range of uses, such as vibration control and structural health monitoring, [54]. In distinction to stacked or connected topologies, which are not considered true Self-sensing actuation, self-sensing actuation options for ionic polymer-metal composites (IPMCs) include monitoring impedance or charge or separating the material into separate actuator and sensor fields.

6. IPMC-INTEGRATED SENSING MECHANISM

IPMCs are employed as sensors that translate mechanical stimuli like bending, pressure, or vibration into electrical impulses, [55]. IPMC, which stands for integrated sensing mechanism, is an acronym given to this approach. This approach takes advantage of IPMCs' electrically active characteristics to provide sensitive, lightweight, and

flexible, [56]. Sensing in realms such as soft automation, medical equipment, and devices for wearing. The internal accessibility of ions in IPMC causes it to generate an electrical signal when triggered externally. It allows distributed structures to sense position, pressure, humidity, motion, and deformation in soft robotics, [57]. Ambient humidity has a big impact on IPMC sensor performance since it can change how they respond electrically. When compared to conventional strip-shaped sensors, novel designs like tube-shaped and gradient-shaped devices have demonstrated increased sensitivity and responsiveness. Analyses that explain energy formation under dynamic pressure reveal that the electrical response of IPMC sensors is controlled by structural dimensions, humidity, and cation type, [58].

Fig. 5. IPMC Sensor System Overview

An IPMC sensor is shown in Figure 5. It transforms mechanical displacement input d(t) into an electrical signal output s(t). The physical properties of the sensor determine its response. To estimate distortion, alternative self-sensing actuation techniques for IPMCs are presented in Table 2, each of which uses distinct electrical attributes. Measurements of stored charge, signal frequency modulation, electrode impedance monitoring, and the separation of actuator and sensor regions on the same material constitute a few of the methods.

Table 2. Integrated Sensing and Actuation Strategies for IPMCs

Reference	How It Works	Integrated Sensing-Actuation Approach
[59]	Detects extension by employing voltage divider and bridge circuits to measure variations in the impedance of the actuator electrode.	Actuation impedance
[60]	Detects variations in impedance brought on by bending using high-frequency signals and the actuation voltage.	Electromechanical Impedance
[61]	Measures the accumulated charge, which indicates the degree of deformation, by momentarily turning off the actuation voltage.	Accumulated Charge on IPMC
[62]	Separates the sensing and actuation regions of the same IPMC material through the formation of electrode patterns.	Dual-Zone Sensor and Actuator Layout

Using high-impedance circuitry, active voltage sensing in IPMCs provides a straightforward design by monitoring the potential difference between electrodes during deformation, [63]. Investigation has consistently shown that although IPMCs
generate identifiable voltage signals when bent, these signals are comparatively weak and affected by variables such as ambient humidity, shape, and hydration. The performance of voltage sensing is limited at shorter frequencies, and improvements through structural and material modifications are frequently required to increase signal quality, even if it is feasible for dynamic applications, particularly above 1 Hz.
The variable voltage sensing frequency response magnitudes seen in different studies [64, 65] are shown in Figure 6. IPMCs exhibit consistent and consistent behavior throughout a wide frequency range when exposed to impact, producing a damped voltage output as a result of fading free vibrations in the form of a sinusoid. Figure 6 shows how the output voltage changes over time. The curves labeled a, b, c, and d track how the IPMC's voltage sensing responds to different conditions—things like excitation frequency, material thickness, solvent types, and how the electrodes are set up. Whenever it comes to deformation sensitivity, IPMC control sensing outperforms conventional sensors like PZT and PVDF, particularly in the 1–100 Hz range, [66]. As a result of high-pass filter effects, sensitivity decreases below 2 Hz, and performance is greatly impacted by solvent type, temperature, and material thickness. The functionality of IPMC control sensing is affected by sample shape, electrode design, and ambient conditions, [67]. It is extremely sensitive to pressure and deformation.

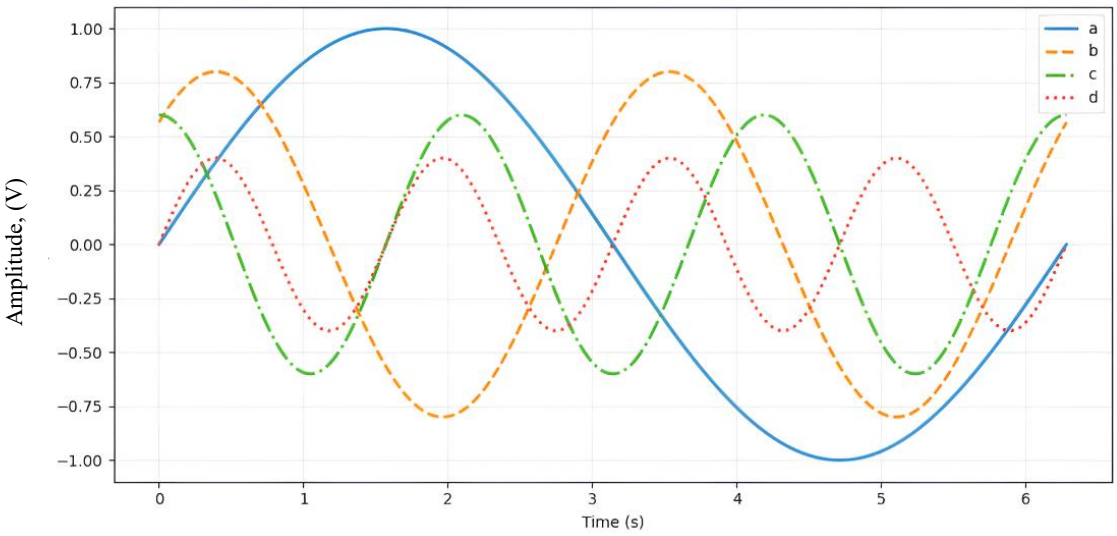

Fig. 6. IPMC Voltage Sensing Frequency Responses Reported

However, circuit constraints, leakage, and charge redistribution cause sensitivity to decrease at low frequencies, requiring compensatory methods like inverse filtering, [68]. Using impedance or charge-based techniques, self-sensing techniques allow for simultaneous actuation and sensing; yet, issues such as signal interference, nonlinearity, and circuit complexity still exist.

7. APPLICATIONS OF IPMCS

IPMCs work by transforming electrical energy into mechanical motion when voltage drives ions within the polymer, resulting in deformation, and they can also work in reverse, generating voltage from mechanical movement, [69]. Depending on the energy conversion direction, they can be employed as actuators in grippers, pumps, and biomimetic devices, or as sensors for bending, flow, energy harvesting, wearable, and humidity monitoring. Ionized polymer membranes with conductive coatings are used to make IPMC actuators, which bend when voltage induces ion movement and osmotic pressure variations, [70]. Their flexibility, low-voltage operation, and bidirectional motion make them popular in biomedical devices, grippers, micro-pumps, and biomimetic robots. Soft robotic grippers, diaphragm micro-pumps, tactile feedback devices, movable intraocular lenses, and robots that imitate creatures like dragonflies, beetles, dolphins, manta rays, caterpillars, and marine life are just a few examples of the many applications, [71].

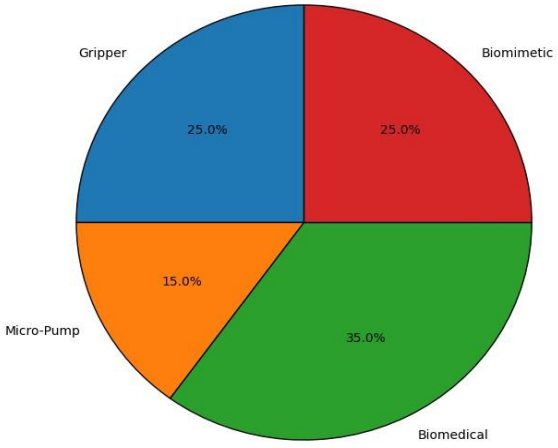

Fig. 7. Distribution of IPMC Applications, with specific proportions for Gripper (25%), Micro-Pump (15%), Biomedical (35%), and Biomimetic (25%), [87]

Figure 7 demonstrates a specific distribution of IPMC applications into four categories: Gripper, Micro-Pump, Biomedical, and Biomimetic. Biomedical applications account for 35% of the market, followed by Gripper and Biomimetic at 25% each, and Micro-Pump at 15%, [85].

Several applications of Ionic Polymer–Metal Composites (IPMCs) in robotics, biomedical engineering, sensing, precision fluid control, and energy systems are compiled in Table 3. Their unique qualities, lightweight, flexible, and low-voltage operation are highlighted, opening the door for developments including wearable sensors, microfluidic devices, artificial muscles, and high-speed bioinspired actuators. Although IPMC actuators are useful for MEMS, robotics, and biomedical devices, mechanical, displacement, and mass transfer issues restrict their performance, [80]. Their actuation is explained and maximized by mathematical models, which can be empirical and physics-based. However, high-accuracy models sometimes require a large amount of processing power. Developments such as forward learning control and self-sensing models, which enable sensor-free operation, provide improved device performance and simplified system design, [81].

Table 3. Application areas of Ionic Polymer–Metal Composites (IPMCs), highlighting their roles in modern manufacturing, biomedical engineering, robotics, sensing, and precision fluid control, based on recent

Application Area	Description & Key Insights
Actuation (Biomimetic & Soft Robotics)	IPMCs are leveraged for their lightweight, large deformation, and low-voltage actuation, enabling applications in bionic robots, soft grippers, underwater actuators, and energy harvesters, [72].
Biomedical Devices	Employed in medical tools such as micro-pumps, soft medical robots, and micro fluidic components with precise low-voltage control, [73].
Sensing & Multi-functional Devices	IPMCs serve as tactile and bending sensors, enabling human motion detection, sign language recognition, gas sensing, and strain sensing. Their multifunctionality also supports intelligent wearable devices, [74].
Precision Flow Control	Used in microfluidic systems—such as micropumps, microvalves, and micromixers—IPMCs enable efficient fluid control in point of-care diagnostics and low-cost bioengineering setups, [75].
Artificial Muscles & Robotics	Due to their ability to mimic muscle-like behavior, IPMCs are used in artificial muscle configurations, robotic manipulators, large bending actuators, and even cryogenic applications, [76].
Energy & Environmental Sensors	Employed in energy harvesting devices, flow sensors, biosensors, humidity sensors, and similar applications where low-voltage responsiveness is an asset, [77].
Advanced Medical Instruments	Latest innovations include IPMC-based catheters capable of multi-degree bending controlled by low driving voltages (∼2.5 V), showcasing potential for precision medical instruments, [78].
Flying Robotics & High-Speed Actuation	IPMCs have been utilized in bionic flying robots, achieving vibration frequencies up to 30 Hz, thanks to enhanced electrode and electrolyte engineering, [79].

8. EMERGING DIRECTIONS IN IPMC DEVELOPMENT

Innovative approaches to IPMCs development emphasize on boosting actuation performance, resilience, and reactivity through composite designs, advanced components, and innovative manufacturing procedures, [82]. For implementation in gathering energy, medicinal gadgets, and soft automation, investigators are also investigating versatile IPMCs. Future IPMC-based creations will be dependent on models that balance application, accuracy, and computing efficiency. Device design innovation, mechanism explanation, and performance efficiency will all be made possible by such models.

This work reviews and contrasts the primary techniques and unique features of the four different categories of IPMC actuator models: nonphysical, partial-physical, physical-based, and application-focused, [83]. Physical-based models succeed in broadness, accuracy, and mechanism explanation but require high configuration effort, computation, and time, while partial-physical models strike a balance with moderate accuracy, complexity, and explanatory power. Figure 8 demonstrates that while nonphysical models are quick and easy to set up, they are less comprehensive, less accurate, and unable to explain IPMC mechanisms, [86]. For the purpose of enhancing accuracy, ability to adapt, and immediate form variable recognition, future research seeks to encompass artificial intelligence, hybrid modeling, and other impacting aspects, including premature ageing. Currently, IPMC actuator models mostly concentrate on minor deformations brought on by sensor constraints.

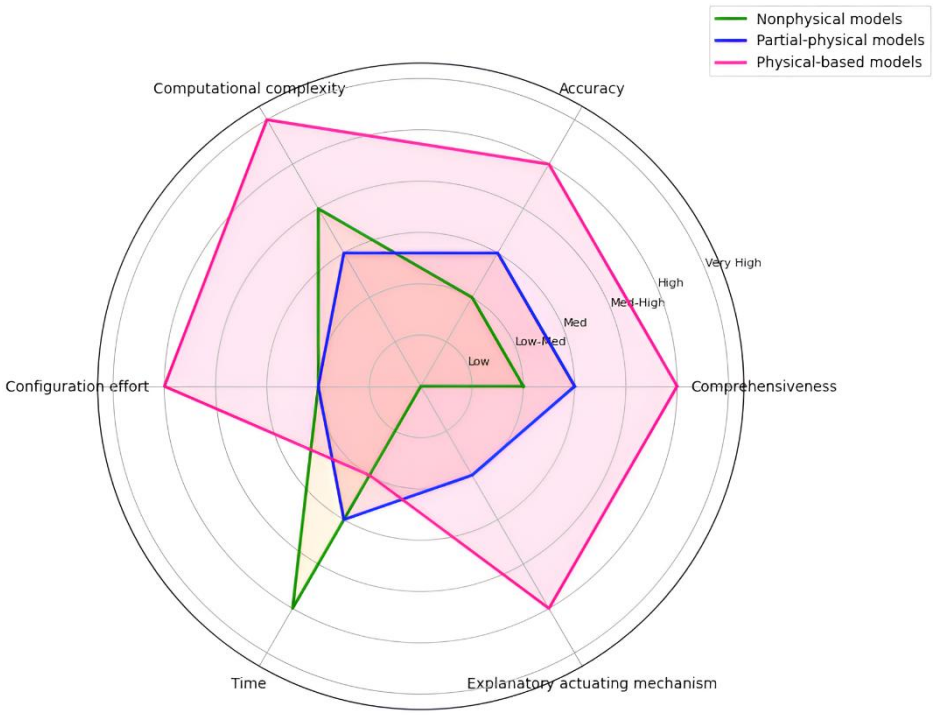

Fig. 8. An evaluation of the accuracy, accuracy, computing complexity, configuration effort, time demand, and explanatory actuating mechanism of nonphysical, partial physical, and physical-based IPMC actuator models is presented in a radar chart

To permit high-performance, complex-shaped IPMC actuators that function dependably in a variety of realistic situations, advances should focus on streamlining intricate PDE (partial differential equation)-based physical models, improving numerical techniques, and closely integrating modeling with device development, [84].

9. CONCLUSIONS

IPMCs have significantly widened their use in biomedical devices, adaptive sensing systems, and soft robotics due to recent manufacturing and regulatory techniques. In alongside advances like nanoparticle-reinforced membranes, enhanced electrode materials, and layered structures, performance gains are the result of careful control over the parameters of the polymer, electrode, and intermediate layer. These techniques improve actuation efficiency, mechanical strength, and conductivity; nevertheless, problems with low output force, relaxation, and short service life still exist. Manufacturing challenges constrain massive amounts of manufacturing, and especially in obtaining repeatable transmembrane pretreatment, managing water content, and striking an appropriate equilibrium between thickness, deformation, and reaction rate. Although they show promise, techniques like solution casting, multilayer integration, and improved pretreatment processes need to be further enhanced for reproducibility and resilience. Modeling, which can be empirical as well as physical-based, is essential to design and regulation since it helps anticipate and control performance. Fortunately, complexities, nonlinearity, and material behavioral variability limit substantial modeling solutions. Sensing techniques hold great promise in environments that are unsuitable for classical actuators, although being less researched than actuation.
Optimizing aspects including membrane thickness, electrode placement, hydration management, and pre-work are essential to obtaining the most dependable technology with the longest endurance. These insignificant modifications made during manufacturing have a significant impact because they increase stability and maintain consistent performance over time. Boosting potential with the integration of communication mechanisms and advancements in active, passive, and self-sensing sensors additionally presents obstructions when it comes of noise reduction and the accuracy of statistical examinations. The knack of IPMC to adapt to various media and situations is further supported by flow sensing investigations. Even with advancements, sustaining consistency and dependable performance over time is still difficult. Legislative activities benefit from the implementation of control models for high-precision purposes and the evaluation of technological variables. Model-based regulation, process optimized performance, and material innovation will need to work together to overcome current limitations. After all the additional investigation, IPMCs play a significant role for future-oriented smart systems of materials.

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