Due to their light weight, flexibility, and low energy consumption, ionic electroactive polymers have become a hotspot for bionic soft robotics and are ideal materials for the preparation of soft actuators. Because the traditional ionic electroactive polymers, such as ionic polymer-metal composites (IPMCs), contain water ions, a soft actuator does not work properly upon the evaporation of water ions. An ionic liquid polymer gel is a new type of ionic electroactive polymer that does not contain water ions, and ionic liquids are more thermally and electrochemically stable than water. These liquids, with a low melting point and a high ionic conductivity, can be used in ionic electroactive polymer soft actuators. An ionic liquid gel (ILG), a new type of soft actuator material, was obtained by mixing 1-butyl-3-methylimidazolium tetrafluoroborate (BMIMBF₄), hydroxyethyl methacrylate (HEMA), diethoxyacetophenone (DEAP) and ZrO₂ and then polymerizing this mixture into a gel state under ultraviolet (UV) light irradiation. An ILG soft actuator was designed, the material preparation principle was expounded, and the design method of the soft robot mechanism was discussed. Based on nonlinear finite element theory, the deformation mechanism of the ILG actuator was deeply analyzed and the deformation of the soft robot when grabbing an object was also analyzed. A soft robot was designed with the soft actuator as the basic module. The experimental results show that the ILG soft robot has good driving performance, and the soft robot can grab a 105 mg object at an input voltage of 3.5 V.

1. Introduction

Traditional robots are typically constructed of rigid motion joints based on hard materials and can perform tasks quickly and accurately. However, such robots have limited movement flexibility and low environmental adaptability and cannot work under space-constrained conditions. These factors limit the application of rigid robots in unstructured and complex environments [1–3].

In nature, mollusks are widely distributed in oceans, rivers, and lakes and on land. After hundreds of millions of years of evolution, this animal has gradually developed the characteristics of a large deformation ability, a light weight, and a high power density ratio and can achieve efficient movement under complex natural environment conditions by changing its body shape. In recent years, researchers have attempted to apply the biological principles of mollusks to the research and design of robotics. A soft robot is composed of a soft material that can withstand large strains, has the capabilities for continuous deformation and drive-structure integration and can arbitrarily change its shape and size over a wide range. Such a robot has strong adaptability to unstructured environments and broad application prospects in military reconnaissance, rescue, and medical surgery [4–6].

A flexible actuator based on an ionic electroactive polymer (EAP) has the advantages of a low driving voltage, a large displacement ability, a light weight, etc. Such actuators have become a research hotspot in the field of bionic robots. In the past few decades, electrochemical actuators, which are substitutes for air- and fluid-derived devices, have been further developed due to their ideal mechanical properties for use in intelligent robots. However, traditional ionic EAP actuators, such as those based on IPMCs, have the characteristics of a short working time in nonwater media,
complex manufacturing process, and a high cost. An ILG is a new type of ionic EAP that can work in air for a long time. Because an ILG offers chemical stability, thermal stability, and simpler ion transport, it is more suitable for the production of soft robot actuators than other EAPs.

In this paper, a soft robot actuator based on an ILG material is proposed and its preparation, driving mechanism, and design method are deeply analyzed. Finally, the validity and rationality of the soft robot are verified by driving performance and grabbing experiments.

2. Design of the ILG Soft Robot

The ILG soft actuator consists of a 5-layer structure, as shown in Figure 1. The middle layer is an electroactive layer composed of the ILG material, which functions to store ionic liquids. The outer two layers that wrap the middle layer are electrode layers, which consist of activated carbon. Activated carbon has a high specific surface area, a high electrical conductivity, a high density, a strong adsorption force, etc., making it very suitable for use as an electrode material [7]. In addition, gold foil is selected as a current collector to cover the surface of the activated carbon layers. When the actuator is working, one end is attached to an external metal electrode, and a wire is led from the external electrode to connect to a power supply.

The soft robot consists of three ILG actuators, a common copper electrode, and three independent copper electrodes, as shown in Figure 2. The input unit consists of a common electrode and an independent electrode. The common electrode is a copper column, with the upper end fixed with a fixture, and the copper electrode is connected to a power source. The soft robot consists of three ILG actuators evenly distributed around the common electrode at 120°. Two copper electrodes sandwich one ILG actuator.

Figure 3 shows the motion cycle of the soft robot to grab an object, which can be described as follows. First, the ILG actuator is naturally stretched, and by applying an input voltage of 3.5 V to the electrodes, the actuator quickly bends outward. Second, when the actuator is close to the target object, the input voltage direction is changed, and the actuator bends inward to clamp the object. Finally, the input signal is changed, and the actuator bends outward to release the object.

2.1. Preparation of the Soft Actuator. The preparation process of an ILG is a process of ionic liquid loading. Ionic liquid loading refers to the immobilization of an ionic liquid to form a solid carrier by physical or chemical means [8]. BMIMBF₄ was selected as the ionic liquid. The carriers of ionic liquids need to have interconnected porous structures, large specific surface area and porosity, and good mechanical strength and electrochemical stability. Therefore, HEMA was selected to prepare the carrier. This material is a colorless and transparent liquid that is soluble in water and has low toxicity. HEMA was polymerized under ultraviolet light to form polyhydroxyethyl methacrylate (PHEMA) with a porous structure.
cause bending deformation, which is the result of the coupling of the electric field, chemical field, flow field, and field force. The average pore diameter of the structure is greater than 10 microns, which is much larger than the diameter of free ions in the ionic liquids (nanoscale). Therefore, BMIM$^+$ and BF$_4^-$ can move freely inside the carrier. Under the action of the electric field, positive and negative ions accumulate in the electrode layers on both sides of the ILG. Because the cation volume is much larger than the anion volume, the volume of the ILG cathode side expands and the volume of the ILG anode side shrinks [11, 12]. The entire actuator therefore bends toward the anode side, as shown in Figure 5.

When an electric field is applied, the movement of the internal ions of the ILG actuator in the porous medium can be described by the Nernst–Planck equation [13]:

$$j_i = -d_i \left( \nabla \omega_i + \frac{F}{RT} \omega_i \nabla \Theta \right),$$

where $i$ is the ion type ($i = 1$ represents the cation, and $i = 2$ represents the anion), $j_i$ is the flow of ions in the PHEMA pores, $d_i$ is the diffusion coefficient of the ions, $\omega_i$ is the ion concentration, $\nabla \omega_i$ is the ion concentration gradient, $\Theta$ is the potential, $\nabla \Theta$ is the potential gradient, $F$ is the Faraday constant, $R$ is the gas constant, $T$ is the absolute temperature, and $z_i$ is the number of ionic charges. The first term on the right-hand side of the formula indicates the contribution of the cation or anion concentration diffusion; the second term indicates the contribution of electromigration.

The continuous equation of concentration changing with time is

$$\frac{\partial \omega_i}{\partial t} = -\nabla j_i,$$

where $\nabla j_i$ is the flow change of the $i$-th ion in the PHEMA pores and $t$ is the time.

The internal electric field balance equation of the ILG actuator can be expressed as follows:

$$E = \frac{D}{k_e} = -\nabla \Theta,$$

$$\nabla D = \rho = F(\omega_1 - \omega_2),$$

where $D$ is the electric displacement, $E$ is the electric field, $\rho$ is the net charge density, and $k_e$ is the effective dielectric constant of the ILG.

The effect of the electrode layer on the bending deformation of the actuator along the width and the thickness is ignored. Considering only the relationship between the axial deformation of the electrode layer and the net charge density, the axial induced strain can be expressed as follows:

$$\varepsilon_c(s) = \rho(s) \alpha(s),$$

where $\varepsilon_c$ is the induced strain, $\alpha(s)$ is the induced strain coupling coefficient, and $s$ is the Laplace domain.

Therefore, the axial induced stress is

$$\sigma_c(s) = \varepsilon_c E_t = \rho(s) d(s),$$

$$d(s) = \alpha(s) E_t,$$

where $E_t$ is the elastic modulus of the electrode layer and $d(s)$ is the axial-induced stress coupling coefficient.

The bending moment of the actuator is

$$M(s) = 2 \int_{b_1}^b \sigma_c(s)xw\,dx = 2 \int_{b_1}^b \rho(s)d(s)xw\,dx,$$

where $b$ and $b_1$ are half the thickness of the actuator and ILG layer, respectively, and $w$ is the width of the actuator.

The ILG actuator is the basic unit of a soft robot and is the source of its deformation. For flexible mechanisms, the degrees of freedom and constraints are determined by the flexibility matrix. The cantilever beam flexibility matrix is as follows [14]:

Figure 4: Fabrication process of the soft actuator: (a) ILG; (b) the activated carbon layer is affixed; (c) the gold foil layer is affixed.

Figure 5: Working principle of the actuator.
3. Hyperelastic Arruda–Boyce Model

Material nonlinearity is caused by the nonlinearity of the constitutive relationship of the material. The constitutive relationship of a material includes the stress, strain, strain rate, load duration, temperature, etc. After a load is unloaded, residual strain will appear in an nonlinear material, as shown in Figure 6.

The hyperelastic Arruda–Boyce model, typically used for relatively largely deformed materials, is used to simulate ILGs. Hyperelastic materials can be described by the strain energy function \( W \), which is used to define the strain energy density in the material. The Arruda–Boyce strain energy function \( W \) is as follows [15–17]:

\[
W = G \sum_{k=1}^{5} \frac{c_k}{\lambda_m^{2(k-1)}} (I_1^k - 3^k) + \frac{1}{D} \left( \frac{I_2}{\lambda_m^2} - \frac{1}{2} \ln I_2 \right),
\]

with \( c_1 = (1/2), c_2 = (1/20), c_3 = (11/1050), c_4 = (19/7000), \) and \( c_5 = (519/673750) \), where \( W \) is the strain energy density, \( G \) is the initial shear modulus, \( \lambda_0 \) is the deformation rate, \( I_2 \) is the elastic volume ratio, and \( D \) is the temperature-dependent material parameter associated with the bulk modulus. A material is completely incompressible when \( \lambda_2 = 1 \).

\( I_1 \) is the first strain invariant of the deviatoric strain, and the relationship between \( I_1 \) and the main tensile strain rates \( \lambda_1, \lambda_2, \) and \( \lambda_3 \) is as follows:

\[
I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2,
\]

\[
I_2 = \frac{1}{\lambda_1^2} + \frac{1}{\lambda_2^2} + \frac{1}{\lambda_3^2},
\]

\[
I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2,
\]

where \( \lambda_1, \lambda_2, \) and \( \lambda_3 \) are the main (extension) deformation rates along the \( x, y, \) and \( z \) directions, respectively. \( I_1, I_2, \) and \( I_3 \) are the relative changes of the length, the surface area, and the volume of the elastomer, respectively.

The material stress is obtained by differentiating the stretching:

\[
\sigma_n = \frac{\partial W}{\partial \lambda_n},
\]

where \( \sigma_n \) is the normal stress and \( \lambda_n \) is the stretching in the loading direction.

The isotropic and incompressible deformation process of an ILG is given by

\[
\sqrt{I_3} = \lambda_1 \lambda_2 \lambda_3 = 1.
\]

When the ILG is uniformly stretched, \( \lambda_2 = \lambda_3 \); equation (11) can be used to calculate

\[
\lambda_2 = \lambda_3 = \frac{1}{\sqrt{\lambda_1}}.
\]

The true stress is obtained by

\[
\sigma_0 = \sigma_n \lambda_n.
\]

Differentiating equation (8), we obtain

\[
\sigma_0 = G \left( \lambda_n^2 - \lambda_n^{-1} \right) + \frac{1}{5 \lambda_m^2} \left( \lambda_n^4 - \lambda_n^{-2} \right) + \frac{11}{175 \lambda_m^2} \left( \lambda_n^6 - \lambda_n^{-3} \right) + \frac{19}{875 \lambda_m^6} \left( \lambda_n^8 - \lambda_n^{-4} \right) + \frac{519}{673750 \lambda_m^{10}} \left( \lambda_n^{10} - \lambda_n^{-5} \right).
\]

4. Model for the Soft Robot. To establish a gripping model scheme as shown in Figure 7, assume that the soft robot is an inextensible, fully flexible elastic rod. Assume that \( I \) is the length of the evenly distributed rod, \( EI \) is the flexural rigidity, \( \rho \) is the mass per unit length, and \( k_g \) is the curvature profile when the object is gripped [18, 19].

4.1. Deformation Analysis for Soft Actuators. At \( s = s^* \), the position of any material point can be represented by the following formula [20], as shown in Figure 8.

\[
\vec{r}(s = s^*) = X(s = s^*)\vec{E}_1 + Y(s = s^*)\vec{E}_2,
\]

where, in Cartesian coordinates, \( X \) and \( Y \) are represented as follows:

\[
\begin{aligned}
X(s = s^*) &= X(s = 0) + \int_0^{s^*} \cos(\theta(\eta))d\eta, \\
Y(s = s^*) &= Y(s = 0) + \int_0^{s^*} \sin(\theta(\eta))d\eta,
\end{aligned}
\]
where \( \eta \) is a dummy variable and \( \theta \) is the angle between the unit tangent vector and the horizontal direction.

\[
\vec{r} = \cos(\theta(s)) \vec{E}_1 + \sin(\theta(s)) \vec{E}_2,
\]

where the prime (\( ' \)) represents the partial derivative with respect to \( s \). Assuming that \( \vec{r} \) is continuous, \( \theta \) and \( \vec{r}' \) are also continuous.

At point \( s = \xi \), the jump in any function \( \chi = \chi(s, \theta(s), \theta'(s)) \) is expressed by a compact notation:

\[
\chi^+ - \chi^- = \lim_{s \uparrow \xi} \chi(s, \theta(s), \theta'(s)) - \lim_{s \downarrow \xi} \chi(s, \theta(s), \theta'(s)).
\]

The jump will be associated with the force applied at the discrete point.

The bending moment \( M \) is described by a constitutive equation:

\[
\vec{M} = EI(\theta' - k_0) \vec{E}_3,
\]

where \( k_0 \) represents the curvature. In addition to the gravity per unit length and end load of the rod, the singular force \( F_\ell \) at \( s = \xi \) must be considered. Figure 7 shows the force that simulates the contact of an object with the soft robot. The governing equation can be derived from the equilibrium of the linear and angular momentum [21–23]:

\[
\begin{align*}
\frac{\partial \vec{m}}{\partial s} + \vec{F}_\ell &= 0, \\
\frac{\partial}{\partial s} (EI(\theta' - k_0) + m_1 \cos(\theta) - m_1 \sin(\theta)) &= 0, \\
\vec{m} + \vec{F}_\ell &= 0,
\end{align*}
\]

where \( \vec{m} = m_1 \vec{E}_1 + m_2 \vec{E}_2 \).

4.2. Deformation Analysis Governing Formula for the Soft Robot. The corner of the object is assumed to be in contact with the soft robot at \( s = \xi \). Two new unit vectors are defined as follows, as shown in Figure 9:

\[
\begin{align*}
\vec{H}_1 &= \cos(\theta(\xi)) \vec{E}_1 + \sin(\theta(\xi)) \vec{E}_2, \\
\vec{H}_2 &= -\sin(\theta(\xi)) \vec{E}_1 + \cos(\theta(\xi)) \vec{E}_2,
\end{align*}
\]

where \( \vec{H}_1 \) is the tangent to the centerline of the soft robot and \( \vec{H}_2 \) is perpendicular to the centerline of the soft robot.

\[
\vec{F}_\ell = f_1 \vec{H}_1 + f_2 \vec{H}_2 = N_1 \vec{E}_1 + N_2 \vec{E}_2,
\]

where \( f_1 \) is the normal force and \( f_2 \) is the corresponding friction force.

Equation (21) is applied to segment \( s \in (\xi, l) \), and we obtain the following equation:

\[
\begin{align*}
\vec{m}(\xi^-) &= -\rho g (l - \xi) \vec{E}_2, \\
\vec{m}(\xi^+) &= N_1 \vec{E}_1 + N_2 \vec{E}_2 - \rho g (l - \xi) \vec{E}_2.
\end{align*}
\]

The expression of the potential energy \( W \) of the soft robot is established:

\[
W = \int_0^l \left\{ \frac{1}{2} EI (\theta'' - k_0)^2 + \rho g Y(s) - \vec{m}(\xi^-) \cdot \vec{r} \right\} ds + \int_\xi^l \left\{ \frac{1}{2} EI (\theta'' - k_0)^2 + \rho g Y(s) \right\} ds,
\]

where

\[
Y(s) = \int_0^s \sin(\varphi(\xi)) d\xi.
\]

Equation (21) can be used to establish boundary value problems:

\[
\begin{align*}
EI(\theta'' - k_0) - \rho g (l - s) \cos(\theta) &= 0, & s \in (0, \xi), \\
EI(\theta'' - k_0) - \rho g (l - s) \cos(\theta) + N_2 \cos(\theta) &= 0, & s \in (\xi, l), \\
- N_1 \sin(\theta) &= 0,
\end{align*}
\]
where the solution $\theta = \theta^*$ satisfies the conditions

$$
\theta(0) = 0,
$$

$$
\theta'(l) = k_0(l),
$$

$$
[\theta]_l = 0,
$$

$$
[\theta]_l = 0,
$$

$$
\int_0^l \cos(\theta(s))ds = \frac{c}{2}.
$$

The soft robot is divided into $K$ segments. The total potential energy expression is approximated as follows:

$$
W_d = \frac{EI}{2} \sum_{i=1}^{K} \left( \frac{\theta_i - \theta_{i-1} - k_0}{ds} \right)^2 ds + \rho g (l - s_0) \sin(\theta_0) \frac{ds}{2}
$$

$$
+ \sum_{i=1}^{K-1} \rho g (l - s_i) \sin(\theta_i) ds + \rho g (l - s_K) \sin(\theta_0) \frac{ds}{2},
$$

$$
- N_1 \cos(\theta_0) \frac{ds}{2} - N_1 \sum_{i=1}^{l-1} \cos(\theta_i) ds - N_1 \cos(\theta_l) \frac{ds}{2},
$$

$$
- N_2 \sin(\theta_0) \frac{ds}{2} - N_2 \sum_{i=1}^{l-1} \sin(\theta_i) ds - N_2 \sin(\theta_l) \frac{ds}{2},
$$

where the constraint function $W_c$ is

$$
W_c = \frac{ds}{2} + \sum_{i=1}^{l-1} \cos(\theta_i) ds + \cos(\theta_l) \frac{ds}{2} - \frac{c}{2}
$$

5. Nonlinear Finite Element Method

Geometric nonlinearity arises from the nonlinear relationship between the strain and displacement. Currently, research on geometric nonlinearity mainly focuses on three types of problems: (1) a large displacement with a small strain, (2) a small displacement with a large strain, and (3) a large displacement with a large strain. A geometric nonlinear problem has two main characteristics. First, due to the large deformation of the structure, the strain and displacement of the structure are nonlinear. Second, a balance equation is established at the position after deformation. In the analysis of large deformation, the displacement of the structure changes continuously and appropriate strain, stress, and constitutive relationships should be adopted.

To capture the nonlinear behavior of the structure, the full nonlinear finite element formulas of the truss elements and beam elements are studied.

5.1. Nonlinear FEM for Truss Elements. In the Cartesian coordinate system, the object is displaced to a certain position under the action of external forces, as shown in Figure 10. $(x_1, y_1, z_1)$ and $(x_2, y_2, z_2)$ are the position co-
ordinates of points $P_1$ and $P_2$ before deformation, respectively. The object is deformed to a new position under the action of external forces. $(u_1, v_1, w_1)$ and $(u_2, v_2, w_2)$ are the deformation coordinates of points $P_1$ and $P_2$ after deformation, respectively.

The formula for the undeformed length of a truss element is as follows:

$$l = \sqrt{(x_2-x_1)^2 + (y_2-y_1)^2 + (z_2-z_1)^2}. \quad (31)$$

The expression of the total Lagrangian strain $\varepsilon$ along the deformation axis is

$$\varepsilon = \frac{\sqrt{(u_2 + x_2 - u_1 - x_1) + (v_2 + y_2 - v_1 - y_1) + (w_2 + z_2 - w_1 - z_1) - l}}{l} \quad (32)$$

According to the change of the elastic energy, the product of the stiffness matrix and the displacement vector is expressed as follows [2, 24]:

$$[k][u] = AIE\varepsilon[\phi],$$

$$[\phi] = \begin{bmatrix} \frac{\partial e}{\partial u} & \frac{\partial e}{\partial v} & \frac{\partial e}{\partial w} \\ \frac{\partial \phi}{\partial u} & \frac{\partial \phi}{\partial v} & \frac{\partial \phi}{\partial w} \\ \frac{\partial \psi}{\partial u} & \frac{\partial \psi}{\partial v} & \frac{\partial \psi}{\partial w} \end{bmatrix}^T,$$

where $E$ is Young’s modulus, $A$ is the cross sectional area, and $l$ is the length of the truss element.

The tangent stiffness matrix is obtained by differentiating equation (33) with respect to the displacement vector:

$$[\bar{k}] = \frac{\partial ([k][u])}{\partial [u]} = EAI[\phi] \frac{\partial e}{\partial [u]} + EAl[\phi] \frac{\partial \varepsilon}{\partial [u]} \quad (34)$$

The mass matrix is the same as that for a linear truss element [25, 26]:

$$[m] = \frac{\rho Al}{6} \begin{bmatrix} 2 & 0 & 0 & 1 & 0 & 0 \\ 0 & 2 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 & 1 \\ 1 & 0 & 0 & 2 & 0 & 0 \\ 0 & 1 & 0 & 0 & 2 & 0 \\ 0 & 0 & 1 & 0 & 0 & 2 \end{bmatrix}. \quad (35)$$

5.2. Nonlinear FEM for Beam Elements. The two famous beam theories are the Euler–Bernoulli and Timoshenko beam theories. The Euler–Bernoulli beam theory assumes that the cross section remains planar and normal to the reference line after bending and its stiffness is higher than the actual stiffness. Timoshenko’s beam theory overcomes this problem by introducing shear deformation into the model, which obtains accurate results for thick beam calculations. Because the soft actuators are slender, the shear deformation is negligible. Therefore, nonlinear Euler–Bernoulli beams with von Karman nonlinearity can be used for modeling and analysis of the soft actuators.

In addition to the bending effect, the finite element formula should also include the torsion and tensile effects to reflect the large deformation effect [27, 28]:

$$\varepsilon_1 = e + z\rho_2 - y\rho_3,$$

$$\varepsilon_2 = -z\rho_1,$$

$$\varepsilon_3 = y\rho_1,$$

$$e = u' + \left(\frac{v'}{2}\right)^2 + \left(\frac{w'}{2}\right)^2,$$

$$\rho_1 = \phi',$$

$$\rho_2 = -w''(1 - (w')^2),$$

$$\rho_3 = -v(1 - (v')^2),$$

where $\varepsilon_{ij}$ is the engineering strain tensor, $e$ is the axial strain, $y$ and $z$ are the coordinates on the cross section, and $\rho_i$ is the deformation curvature. $u$, $v$, and $w$ are the displacements on the cross section.

When a change of energy is applied, the product of the stiffness matrix and the displacement vector is expressed as follows:

$$[k][h] = \int_I [B]^T [\Psi]^T [\Phi][\phi] dx, \quad (37)$$
where
\[
[B] = \frac{\partial[N]}{\partial s},
\]
\[
[\Psi] = \begin{bmatrix}
1 & \nu' & w' & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 2w'' & 0 & 0 & -\left(1-(w')^2\right) \\
0 & -2\nu'w'' & 0 & 0 & 1-(\nu')^2 & 0
\end{bmatrix},
\]
\[
[\Phi] = \begin{bmatrix}
EA & 0 & 0 & 0 & 0 & 0 \\
0 & GI_{11} & 0 & 0 & 0 & 0 \\
0 & 0 & EI_{22} & 0 & 0 & 0 \\
0 & 0 & 0 & EI_{33} & 0 & 0
\end{bmatrix},
\]
\[
\{\phi\} = \begin{bmatrix}
e \\
\rho_1 \\
\rho_2 \\
\rho_3
\end{bmatrix}.
\]

Assume that
\[
\{h^{(i)}\} = \{\bar{F}\} + \Delta h^{(i)}.
\]

(38)

By applying Taylor expansion without higher order terms, the tangential stiffness matrix is expressed as follows:
\[
[k] = \int [B]^T [\Psi]^T [\Phi] [\Psi] + [\Gamma] [B] dx,
\]
where
\[
[\Gamma] = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & EAe - 2EI_{33}w'' & 0 & 0 & -2EI_{33}\nu' & 0 \\
0 & 0 & EAe + 2EI_{22}w'' & 0 & 0 & 2EI_{33}w' \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}.
\]

(41)

Assume that
\[
\{F\} = \lambda \{\bar{F}\},
\]
where \(\lambda\) is the load parameter and \(\bar{F}\) is the preselected load vector.

5.3. Nonlinear Convergence Algorithms. Although the Newton–Raphson algorithm is used for nonlinear static analysis, the tangent stiffness matrix becomes singular at some points, which makes a global equilibrium solution impossible. Riks proposed a process to track the intersection of the normal to the tangent line with the equilibrium path to solve this problem [29], as shown in Figure 11. The Crisfield method uses arcs instead of vertical lines to search for solutions. The increment of the load factor becomes an unknown problem to be solved in the iterative process.
where $\vec{U}$ is the displacement vector.

\[
[k] \begin{bmatrix} \vec{U} \end{bmatrix} \begin{bmatrix} \vec{U} \end{bmatrix} + [k_T] \begin{bmatrix} \vec{U} \end{bmatrix} \begin{bmatrix} \vec{U} \end{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_1 + \begin{bmatrix} \vec{F} \end{bmatrix} \delta \lambda_1 = 0, \tag{44}
\]

where $\delta \begin{bmatrix} \vec{U} \end{bmatrix}_1$ is the first increment of the load parameter in the $i$-th step and $\delta \lambda_1$ is the first increment of the displacement vector in the $i$-th step.

\[
\begin{bmatrix} \vec{U} \end{bmatrix}_1 = \begin{bmatrix} \vec{U} \end{bmatrix}^{i-1} + \delta \begin{bmatrix} \vec{U} \end{bmatrix}_1, \tag{45}
\]

\[
\lambda_1 = \lambda^{i-1} + \delta \lambda_1. \tag{46}
\]

Substituting (45) and (46) into equation (44), we obtain

\[
[k] \begin{bmatrix} \vec{U} \end{bmatrix} \begin{bmatrix} \vec{U} \end{bmatrix} - \lambda_1^{i-1} \begin{bmatrix} \vec{F} \end{bmatrix} + [k_T] \begin{bmatrix} \vec{U} \end{bmatrix} \lambda_1^{i-1} \begin{bmatrix} \vec{F} \end{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_1 + \begin{bmatrix} \vec{F} \end{bmatrix} \delta \lambda_1 = 0. \tag{47}
\]

When the second step incremental search path is perpendicular to the normal of the first step incremental path, we obtain

\[
\delta \begin{bmatrix} \vec{U} \end{bmatrix}_1 \cdot \delta \begin{bmatrix} \vec{U} \end{bmatrix}_2 + \begin{bmatrix} \vec{F} \end{bmatrix} \delta \lambda_1 \cdot \begin{bmatrix} \vec{F} \end{bmatrix} \delta \lambda_2 = 0. \tag{48}
\]

When solving nonlinear finite element equations by an iterative method, choosing the appropriate convergence criterion is necessary to ensure that the iteration can be terminated. The convergence criterion will directly affect the speed and accuracy of the solution. If the convergence criterion is not appropriately chosen, the calculation will fail.

From equations (47) and (48), we obtain

\[
\begin{bmatrix} \vec{U} \end{bmatrix}_1 = \begin{bmatrix} \vec{U} \end{bmatrix}^{i-1} \begin{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_1 \end{bmatrix} \begin{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_1 \end{bmatrix} + \begin{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_2 \end{bmatrix} \begin{bmatrix} \delta \begin{bmatrix} \vec{U} \end{bmatrix}_2 \end{bmatrix} = 0. \tag{49}
\]

The convergent load parameters and displacement vectors are as follows:

\[
\lambda_i = \lambda^{i-1} + \delta \lambda_1 + \delta \lambda_2 + \cdots, \tag{50}
\]

\[
\begin{bmatrix} \vec{U} \end{bmatrix}_i = \begin{bmatrix} \vec{U} \end{bmatrix}^{i-1} + \delta \begin{bmatrix} \vec{U} \end{bmatrix}_i + \delta \begin{bmatrix} \vec{U} \end{bmatrix}_2 + \delta \begin{bmatrix} \vec{U} \end{bmatrix}_3 + \cdots.
\]

6. Experimental Analysis

6.1. Stress Calculation of the ILG. To verify the accuracy and practicability of the induced stress expression of the ILG, the deformation rate of each point in the uniaxial tensile test is substituted into the stress expression to calculate the stress.

For the Arruda–Boyce model, the parameters $G$ and $\lambda_m$ are as follows:

\[
G = 4.10736, \quad \lambda_m = 4.62529. \tag{51}
\]

6.2. Experiment on the Soft Actuator. The square wave of the input signal has a magnitude of 4 V, a period of 30 s, and a duty cycle of 50%. The actuator size is 30 mm × 5 mm × 0.5 mm, the free segment length is 25 mm, and the average thickness of the ILG layer is approximately 0.4 mm.

Figure 12 shows that the first half of the stress-strain curve calculated by the Arruda–Boyce model almost coincides with the experimental curve, while for the second half, the relative error between the calculated and experimental stress-strain curves becomes increasingly larger but remains small. The above analyses indicate that the calculation formula of the ILG stress is feasible and reliable.
Table 1: Comparison of the tensile stress calculation data with experimental data obtained in the uniaxial tensile test.

| Force (mN) | Deformation (mm) | Strain (%) | Stress (kPa) | Calculated stress ($\sigma_E$) (kPa) | Error (%) |
|------------|------------------|------------|--------------|--------------------------------------|-----------|
| 4.97       | 2.0              | 5.7        | 0.50         | 0.54                                 | 7.42      |
| 8.21       | 3.5              | 10         | 0.86         | 0.92                                 | 6.64      |
| 14.88      | 7.0              | 20         | 1.70         | 1.78                                 | 4.70      |
| 20.52      | 10.5             | 30         | 2.54         | 2.64                                 | 4.08      |
| 25.35      | 14.0             | 40         | 3.38         | 3.53                                 | 4.38      |
| 29.47      | 17.5             | 50         | 4.21         | 4.43                                 | 5.21      |
| 33.06      | 21.0             | 60         | 5.04         | 5.34                                 | 6.02      |
| 36.22      | 24.5             | 70         | 5.86         | 6.26                                 | 6.69      |
| 38.94      | 28.0             | 80         | 6.68         | 7.16                                 | 7.31      |
| 41.48      | 31.5             | 90         | 7.50         | 8.06                                 | 7.40      |
| 43.58      | 35.0             | 100        | 8.30         | 8.94                                 | 7.70      |
| 45.50      | 38.5             | 110        | 9.10         | 9.80                                 | 7.65      |
| 47.13      | 42.0             | 120        | 9.88         | 10.63                                | 7.64      |
| 48.67      | 45.5             | 130        | 10.65        | 11.44                                | 7.26      |
| 49.98      | 49.0             | 140        | 11.41        | 12.21                                | 6.93      |
| 51.03      | 52.5             | 150        | 12.15        | 12.96                                | 6.71      |
| 51.95      | 56.0             | 160        | 12.86        | 13.69                                | 6.39      |
| 52.75      | 59.5             | 170        | 13.56        | 14.38                                | 6.02      |
| 53.40      | 63.0             | 180        | 14.24        | 15.05                                | 5.66      |
| 53.90      | 66.5             | 190        | 14.89        | 15.69                                | 5.36      |
| 54.32      | 70.0             | 200        | 15.52        | 16.30                                | 5.01      |
| 54.65      | 73.5             | 210        | 16.12        | 16.88                                | 4.65      |
| 54.78      | 77.0             | 220        | 16.70        | 17.44                                | 4.50      |
| 54.86      | 80.5             | 230        | 17.25        | 17.98                                | 4.31      |
| 54.94      | 84.0             | 240        | 17.78        | 18.50                                | 3.97      |
| 54.84      | 87.5             | 250        | 18.28        | 18.99                                | 3.88      |
| 54.72      | 91.0             | 260        | 18.74        | 19.46                                | 3.72      |
| 54.47      | 94.5             | 270        | 19.18        | 19.91                                | 3.73      |
| 54.01      | 98.0             | 280        | 19.57        | 20.34                                | 4.06      |
| 53.61      | 101.5            | 290        | 19.93        | 20.75                                | 4.22      |
| 53.23      | 105.0            | 300        | 20.24        | 21.15                                | 4.29      |
| 52.48      | 108.5            | 310        | 20.50        | 21.53                                | 5.05      |
| 51.83      | 112.0            | 320        | 20.73        | 21.89                                | 5.59      |
| 51.02      | 115.5            | 330        | 20.91        | 22.23                                | 6.42      |
| 50.29      | 119.0            | 340        | 21.04        | 22.57                                | 7.09      |
| 49.21      | 122.5            | 350        | 21.12        | 22.88                                | 8.51      |

Figure 12: Comparison of the tensile stress calculation data with experimental data obtained in the uniaxial tensile test.
Figure 13: Soft actuator motion screenshots when the input voltage is 4V.

Figure 14: (a–c) Displacement calculation results for the input voltages of 3V, 3.5V, and 4V, respectively.
The current response stability of the soft actuator is tested by applying a square wave signal with a magnitude of 4 V, a period of 30 s, and a duty cycle of 50%, and the current response curve is shown in Figure 16. The experimental results show that the current peaks remain unchanged over 30 minutes, and the current response of the ILG actuator is stable. Therefore, the internal electrolyte is not substantially decomposed.

From the above experiments, the ILG actuator can maintain stable current response and bending displacement in air. These results show that the ILG actuator can effectively avoid the defects of traditional EAP actuators and has excellent driving performance.

6.4. Experiment of the Soft Robot Grabbing an Object.
First, an input voltage of 3.5 V is applied across the electrodes, and the soft robot gradually opens outward. Next, the operating platform is moved close to the target object. Finally, by changing the direction of the supply voltage, the soft robot reversely bends to clamp the object.

| Force (V) | 3.0 | 3.5 | 4.0 |
| Deformation (mm) | 3.7 | 4.3 | 5.0 |

Table 2: Displacement calculation results for the different input voltages.
The parameters of the soft robot are shown in Table 3. The values 1 to 3 in the first column are the ILG actuator number, corresponding to the three sets of execution components on the manipulator, with a total mass of 211 mg.

A set of screenshots of the soft robot manipulator’s experimental process is shown in Figure 17. The process of the soft robot grabbing an object is shown in Figure 3. From Figures 17(a) and 17(b), when no object is grabbed, the deformation of the soft actuator is larger, and the deformation is similar to that in Figure 13. In this case, the mass of the object clamped by the soft robot at an input voltage of 3.5 V is approximately 105 mg. The experiments verify the effectiveness of ILG soft robots.

Compared with the soft robot designed by Saito et al., which has a load capacity of approximately 3 mg, the ILG soft robot designed in this paper has a greatly increased load capacity. Since the soft robot consists of three actuators, this ILG soft robot has better adaptability for grabbing complex shape objects than Saito’s soft robot, which consists of two actuators [31].

In addition, the service life is an important performance indicator for EAP robots. The ILG material avoids the defects of IPMCs, and the soft robot proposed in this paper can theoretically work in air for a long time.

### 7. Conclusions

A soft robot is a new flexible structure, and the materials and mechanism design methods of a soft robot are quite different from those of traditional robots. To avoid the shortcomings of traditional rigid manipulators, such as large energy consumption and complex mechanisms, a soft robot based on a new ILG material is proposed in this paper.

A high-performance ILG actuator based on the principle of light curing was developed, and a modular design method based on motion and constraints was discussed. An ion transport model of porous media based on the Nernst–Planck equation was established, and the deformation mechanism of the ILG actuator was deeply analyzed in combination with the theory of cantilever beam deformation. Based on nonlinear finite element theory, the deformation of the soft robot when grabbing an object was analyzed. A three-finger type soft robot was designed, and the maximum displacement was 5 mm at a 4 V square wave voltage. The soft robot can grab a 105 mg object under a 3.5 V voltage. The results prove that the ILG bionic soft robot has good development prospects.

| Number | Total length (mm) | Mass (g) | Free segment length (mm) | Width (mm) | Total thickness (mm) | ILG layer thickness (mm) |
|--------|------------------|---------|--------------------------|------------|---------------------|------------------------|
| 1      | 35               | 0.068   | 30                       | 5          | 0.5                 | 0.4                    |
| 2      | 35               | 0.070   | 30                       | 5          | 0.5                 | 0.4                    |
| 3      | 35               | 0.073   | 30                       | 5          | 0.5                 | 0.4                    |

Figure 17: Screenshots of the soft robot grabbing an object. (a) Natural stretching. (b) Bending inward. (c) Bending outward. (d) Grabbing an object.
Data Availability
The data used to support the findings of this study are included within the article.

Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this paper.

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