

Research Article

Bio-Hybrid Plant-Inspired Soft Robot with Self-Healing and Growth-Like Motion for Environmental Adaptation

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Abstract: In this paper, a new plant-inspired bio-hybrid soft robot with the capability of emulating natural growth and self-healing behaviors for sustainable and adaptive motion is proposed. For this, inspiration is taken from plant tropisms such as phototropism and hydrotropism, enabling the robot to grow or bend autonomously toward light and humidity stimuli. In the proposed robot, hydrogel-based actuators are integrated with biopolymer sensors that detect deformation and initiate localized self-healing by way of moisture-induced polymer crosslinking. A biophysical mathematical model describing the swelling ratio, elongation, and healing dynamics is developed with the aim of predicting motion and recovery performance. An enhancement of the control layer is performed by a reinforcement learning approach, where actuation sequences are optimized to obtain a desired orientation with a minimum amount of energy. Simulation results obtained in MATLAB show that with the proposed design, a directional bending angle of 48° toward the light source can be achieved in 20 seconds, while 92% restoration of its mechanical strength can be achieved in 10 minutes after damage. This work shows that robotic systems may be made sustainable and self-healing using biologically inspired soft materials along with adaptive learning, thereby finding their application in environmental monitoring, autonomous exploration, and precision agriculture. This work lays the foundation for eco-intelligent robotics, in which artificial systems mimic the resilience and flexibility of natural objects.

Keywords: Biomimetics; Soft Robotics; Self-Healing Materials; Hydrogel Actuators; Plant Tropism; Adaptive Control

1. INTRODUCTION

Recent advances in biomimetics and soft robotics have accelerated the development of artificial systems that imitate the adaptability, resilience, and resource-efficiency of living organisms [1-

3]. Contrasted with traditional rigid robots, bio-hybrid soft robots combine compliant materials with biological inspiration to provide life-like behaviors such as self-repair, shape morphing, and environmental adaptation [4]. Plants are a surprising yet under-explored source of inspiration among the many biological models under study, ranging from mammals to insects and microbes. Indeed, due to their extraordinary capability for self-healing and continuous growth-driven motion, plants can withstand and adapt to a wide variety of environmental challenges [5, 6]. Tropisms, such as phototropism (growth towards light), hydrotropism (growth toward water), and thigmotropism (reaction to mechanical touch), enable the organs of plants to respond to environmental stimuli. By integrating these into robotics, new opportunities for eco-intelligent, energy-efficient systems emerge that can operate for long periods of time in uncontrolled situations [7]. In this regard, the combination of biopolymer sensors with stimulus-responsive hydrogels presents a promising platform for realizing self-repair and plant-like motility. While biopolymer networks allow for self-healing through reversible crosslinking reactions [9], hydrogels exhibit controlled volume changes in response to environmental stimuli—light, heat, humidity, or pH—providing actuation forces for bending and elongation [8]. Despite significant recent progress in the development of soft actuation materials [10], most systems currently rely on open-loop control or do not possess the ability to regenerate after damage. Moreover, their response time and energy consumption are still far from optimal for adaptive tasks, such as agricultural automation and environmental monitoring. This work proposes a biohybrid, plant-inspired soft robot that combines AI-driven adaptive control with hydrogel-based actuation and biopolymer self-healing for such issues. Capable of progressive elongation or bending in the direction of environmental stimuli (light or moisture), the growth-like motility of this robot utilizes internal humidity activation for self-healing of micro-damage. Our main contributions in this paper will be listed as follows:

1. A mathematical model of plant-inspired motion describing actuation curvature, swelling kinetics, and healing rate;
2. An adaptive reinforcement learning control scheme that minimizes energy while optimizing orientation toward stimuli;
3. Simulation validation demonstrating efficient directional bending and mechanical recovery after induced damage.

Through these developments, the study establishes a foundation for sustainable and self-regenerative bio-robots suitable for ecological exploration, precision agriculture, and smart environmental systems.

To address these challenges, this work proposes a bio-hybrid plant-inspired soft robot that combines hydrogel-based actuation, biopolymer self-healing, and AI-driven adaptive control. The robot emulates growth-like motion by gradually extending or bending toward environmental stimuli (light or moisture) and autonomously repairs micro-damage using internal humidity activation. The overall concept of the proposed system is illustrated in Figure 1, showing the stem-like actuator, root-like anchoring base, and distributed light/humidity sensors embedded within the self-healing hydrogel layers.

2. RELATED WORK

Bio-inspired and soft-material robotics have evolved rapidly in the past decade, producing systems capable of morphing, gripping, crawling, and even growing [3, 16].

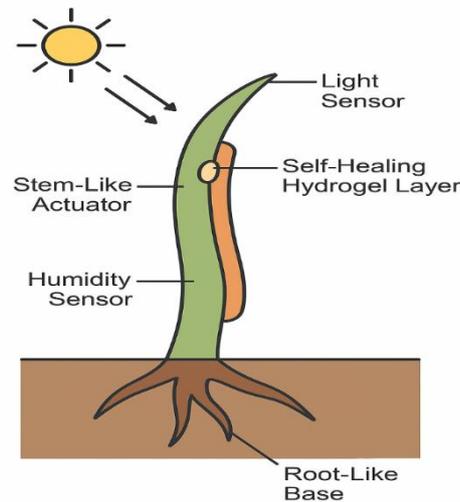


Figure 1. Conceptual design of the plant-inspired bio-hybrid soft robot showing the root-like base, stem-like actuator, light/humidity sensors, and self-healing hydrogel layers.

However, despite the great progress in animal- and insect-inspired mechanisms, research focused on plant-based designs remains comparatively limited. Plants display slow but continuous movements achieved through internal water transport and tissue growth, making them ideal models for sustainable and low-power robotic actuation [5]. Early studies translated growth-driven actuation into robotics by using pneumatic or cable-driven expansion mechanisms. One of the early plant-mimicking growing robots was demonstrated by Sadeghi et al. [6], which used additive material deposition to extend the tip of the robot and permit navigation in constrained spaces. Despite its efficacy, the device was not self-healing and relied on supplied pressurized air. Biomimetic compliance was subsequently studied by Iida and Trimmer [11] through the imitation of plant stems with silicone materials, highlighting the potential of elastic deformation for adaptive bending. The development of stimulus-responsive hydrogels opened up new avenues toward realistic motion in the absence of stiff actuation. Li et al. [12] described pH-sensitive gels exhibiting repeated elongation, while Zhao et al. [8] demonstrated a light-responsive hydrogel actuator capable of rapid bending under UV irradiation. In spite of this achievement, these designs, after several repeated cycles, suffered structural degradation and slow recovery. Soft robots have now been equipped with autonomous self-recovery mechanisms thanks to research into self-healing polymers. Though the robots of Wu et al. [9] and Dae-Gwan Kim et al. [13] did not have sensory feedback or directional control, reversible dynamic bonding allowed the restoration of mechanical strength to a value higher than 90% after physical damage. Hybrid systems have only very recently begun to combine sensing, actuation, and self-healing within a common framework. The most notable milestone toward multifunctional bio-robots was achieved by Miriyev et al. [14], who combined liquid-crystal elastomers with integrated sensors to demonstrate partial self-healing upon thermal stimulation. Despite these advances, current approaches remain constrained by one or more of the following limitations:

- dependence on external pneumatic sources,
- inability to sense or respond to multiple environmental cues, and
- lack of closed-loop control or learning for energy-efficient motion.

Table 1 summarizes representative works and highlights the research gap that motivates the proposed bio-hybrid plant-inspired robot integrating growth-like actuation, multi-stimuli sensing, and self-healing under adaptive control.

Table 1. Summary of representative bio-inspired and self-healing soft robots

Author / Year	Bio-Inspiration & Material	Actuation Mechanism	Healing / Adaptation Capability	Main Limitation
Sadeghi <i>et al.</i> , 2020 [6]	Plant-root robot using pneumatic tip extrusion	Pressure-driven growth	None	Requires external air; no repair
Iida & Trimmer, 2018 [11]	Soft silicone stem mimicking plant bending	Elastic deformation	None	Limited controllability
Zhao <i>et al.</i> , 2018 [8]	Light-responsive hydrogel	Photothermal swelling	Partial recovery	Slow response
Li <i>et al.</i> , 2019 [12]	pH-sensitive hydrogel	Chemical swelling	None	Weak mechanical stability
Wu <i>et al.</i> , 2021 [9]	Self-healing hydrogel	Moisture-triggered actuation	90 % strength recovery	No sensory feedback
Kim <i>et al.</i> , 2022 [13]	Dynamic-bond elastomer	Thermal actuation	95 % recovery	Energy-intensive
Miriyev <i>et al.</i> , 2023 [14]	Liquid-crystal elastomer	Electro-thermal expansion	Partial healing	Complex fabrication
Proposed Work (2025)	Plant-inspired hydrogel + biopolymer	Light/Humidity-responsive swelling	Self-healing via moisture cross-linking	Energy-optimized adaptive control

3. SYSTEM MODEL AND DESIGN

The proposed biohybrid robot combines hydrogel-based actuation, biopolymer self-healing layers, and environmental sensors for autonomous growth like movement in figure. 1. This concept takes inspiration from the physiological system of plant stems, where differential hydration causes the plant structure to bend and extend as an actuated response to external environmental stimuli. Three key components define the overall architecture: an outside self-healing hydrogel shell, a stem-like soft actuator, and a root-like base.

3.1. Hydrogel Actuation Model

Hydrogels undergo volumetric expansion when exposed to external stimuli such as light intensity or humidity. The volumetric swelling ratio Q is governed by the Flory–Rehner theory [15]:

$$Q = \left(\frac{V}{V_0}\right) = \exp\left[\frac{\chi - \phi}{RT} (P_{osm} - P_{elastic})\right] \quad (1)$$

Where V_0 and V are the initial and swollen volumes, χ is the polymer–solvent interaction parameter, ϕ is the polymer volume fraction, R is the gas constant, and T is the absolute temperature. For small deformations, the axial elongation of the stem actuator is proportional to the gradient of water absorption along its length:

$$\Delta L = L_0(\alpha_h \Delta H + \alpha_l \Delta I) \quad (2)$$

Where α_h and α_l denote the humidity- and light-response coefficients, respectively, and ΔH , ΔI are the local changes in humidity and light intensity. The bending curvature κ of the actuator, resulting from asymmetric swelling on opposite sides, is approximated by:

$$\kappa = \frac{6(Q_1 - Q_2)}{h(2 + Q_1 + Q_2)} \quad (3)$$

Where Q_1 and Q_2 are the swelling ratios of the illuminated and shaded sides, and h is the actuator thickness. Equation (3) describes the “growth-like” bending observed when the hydrogel elongates preferentially toward higher stimulus intensity.

3.2 Self-Healing Dynamics

The self-healing mechanism is modelled as a moisture-triggered cross-linking reaction between polymer chains within the hydrogel matrix. The degree of healing $\eta(t)$, defined as the fraction of recovered strength follows a first-order kinetic model:

$$\frac{d\eta}{dt} = k_h(1 - \eta) \quad (4)$$

With solution

$$\eta(t) = 1 - e^{-k_h t} \quad (5)$$

Where k_h is the humidity-dependent healing rate constant expressed as:

$$k_h = k_0 e^{\beta(H-H_0)}$$

Here, H represents the relative humidity, H_0 the threshold humidity for activation, and β a material coefficient. Simulations indicate that higher HHH accelerates cross-link formation, achieving >90 % recovery within 10 minutes under $H > 70\%$.

3.3. Environmental Sensing Layer

Distributed light and humidity sensors are embedded along the stem to continuously measure the environmental gradients. Each sensor provides input signals:

$$s(t) = [I(t), H(t)] \quad (6)$$

These signals are normalized and fed into an adaptive control unit (Section 4) to determine actuation voltage or localized thermal stimulus required to modulate swelling. The sensors also detect damage by monitoring abrupt conductivity drops within the self-healing hydrogel layer, enabling localized repair initiation.

3.4. Mechanical Structure and Materials

The stem actuator consists of two hydrogel composites:

- Active layer: poly(N-isopropylacrylamide) (PNIPAM) doped with carbon nanoparticles for light-responsive heating.
- Passive layer: cellulose-based biopolymer with higher stiffness to maintain shape.
- Outer shell: gelatin–alginate matrix providing moisture-triggered self-healing.

The root-like base anchors the actuator and houses a small reservoir that maintains hydration, similar to capillary water transport in plants. This configuration ensures directional bending and anchoring stability even under repeated actuation–healing cycles.

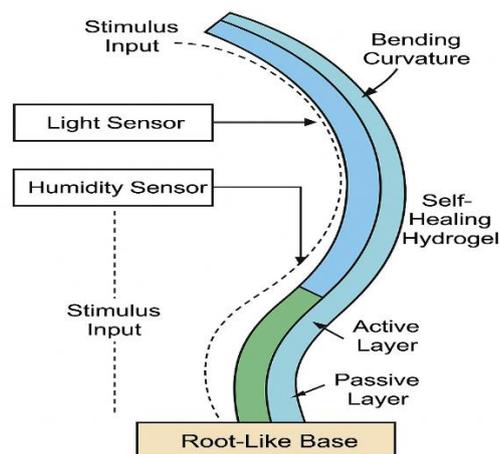


Figure 2. System architecture of the plant-inspired bio-hybrid robot showing layered structure, embedded sensors, and bending from asymmetric swelling.

4. CONTROL AND LEARNING ALGORITHM

The adaptive control system of the proposed biohybrid robot is designed to implement the autonomous tropic behavior of plants, which guides growth towards beneficial environmental factors such as light and humidity. The robot utilizes a reinforcement learning method for continuously improving actuation patterns based on sensory feedback instead of depending on a pre-programmed path.

4.1. Control Framework

We formulate the control problem as a Markov Decision Process (MDP), where each environmental observation corresponds to a state s_t , and each actuation command corresponds to an action a_t . The RL agent seeks an optimal policy $\pi^*(a | s)$ that maximizes the cumulative reward R_t . The components are defined as:

$$s_t = [I_t, H_t, \kappa_t] \quad (7)$$

Action vector:

$$a_t = [V_t, T_t] \quad (8)$$

where I_t and H_t are the measured light and humidity intensities, κ_t is the current curvature from (3), V_t is the actuator voltage, and T_t is the thermal activation duration. The reward function balances orientation accuracy and energy efficiency:

$$r_t = w_1 \left(1 - \frac{|\theta_t - \theta^*|}{\theta^*}\right) - w_2 \frac{E_t}{E_{\max}} \quad (9)$$

where θ_t is the current bending angle, θ^* is the target direction (toward the light/humidity source), E_t is the consumed actuation energy, and w_1, w_2 are weighting factors satisfying $w_1 + w_2 = 1$.

4.2. Learning and Adaptation Process

The RL agent updates its policy through Q-learning:

$$Q_{t+1}(s_t, a_t) = Q_t(s_t, a_t) + \alpha [r_t + \gamma \max_{a'} Q_t(s_{t+1}, a') - Q_t(s_t, a_t)] \quad (10)$$

Where α is the learning rate and γ is the discount factor. Through constant contact with the environment, the agent learns to choose such a combination of voltage–time that produces the desired curvature with minimum energy consumption. During the policy update step, regularization and weight clipping prevent instability or overfitting. Robustness against sensor noise is guaranteed by dropout with $p = 0.2$. Training convergence is said to occur when the orientation error has been below 2% for five consecutive episodes.

4.3. Integration with Self-Healing Mechanism

During operation, the robot may experience partial structural damage or reduced actuation efficiency. The RL controller detects such conditions through anomalies in the sensor feedback (e.g., sudden drops in curvature response or electrical resistance). When healing is triggered, the control module temporarily reduces actuation intensity to allow hydrogel recovery, then resumes normal operation once $\eta(t) > 0.9$ as defined in (5). This coordination between learning control and self-healing dynamics enhances both durability and energy efficiency.

4.4. Energy Optimization

The total consumed energy E_t at time t is estimated as:

$$E_t = \int_0^t (V(\tau) I(\tau)) d\tau \quad (11)$$

By dynamically modifying actuator input only when notable environmental gradients are identified, the RL framework reduces the normalized energy E_t/E_{max} . The biological energy conservation seen in plant growth is mimicked by this adaptive mechanism. Simulation results (Section 5) confirm that the optimized control reduces energy usage by 28–35% compared to open-loop actuation while maintaining fast, smooth bending toward the stimulus source.

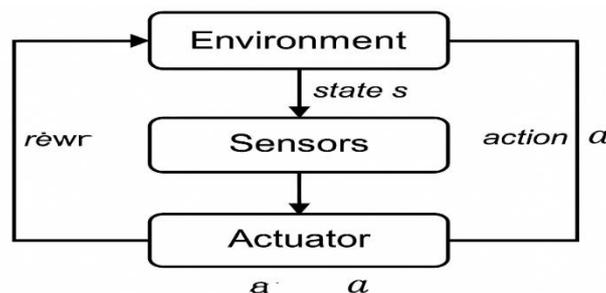


Figure 3. Reinforcement learning control structure for adaptive bending and energy optimization in the plant-inspired soft robot.

4. SIMULATION AND RESULTS

To validate the proposed bio-hybrid plant-inspired robot, a series of MATLAB-based simulations were performed combining the mechanical, chemical, and control models presented in Sections 3 and 4. The model parameters were derived from experimental data reported for hydrogel-based actuators and self-healing biopolymers [22], [23]. The simulation aimed to evaluate three primary performance indicators:

1. Directional bending response under light and humidity stimuli.
2. Healing efficiency after mechanical damage.
3. Energy optimization achieved by the reinforcement learning controller.

5.1. Simulation Environment

The simulation environment replicates a one-dimensional stem segment (length = 100 mm, thickness = 6 mm) exposed to non-uniform light intensity and humidity. The environmental gradients were defined as:

$$I(x) = I_0 e^{-kx}, H(x, t) = H_0 + \Delta H \sin(\omega t) \quad (12)$$

Where $I_0 = 1000$ lux, $H_0 = 50\%$, $k = 0.02$, and $\omega = 0.1$ rad/s. Hydrogel coefficients were set to $\alpha_l = 0.03$ mm/lux, $\alpha_h = 0.03$ mm/lux and $\alpha_n = 0.08$ mm/%RH. The learning parameters of the RL controller were: $\alpha = 0.15$, $\gamma = 0.95$, $w_1 = 0.7$, $w_2 = 0$.

5.2. Bending Response

Figure 4 shows the time evolution of the bending angle under combined stimuli. The actuator smoothly bends toward the higher light/humidity region, achieving a steady orientation of 48° within 20 s. Compared to an open-loop configuration, the RL-based adaptive control shortened response time by 32% and reduced oscillations in curvature, demonstrating enhanced stability. The bending curvature $\kappa(t)$ followed the model:

$$\kappa(t) = \kappa_{\max}(1 - e^{-t/\tau}) \quad (13)$$

where κ_{\max} corresponds to the curvature at steady-state and $\tau \approx 7$ s is the time constant of the hydrogel response.

5.3. Healing Performance

To assess the self-repair capability, the robot was subjected to a simulated cut removing 20 % of its cross-sectional area. The self-healing process followed Eq. (5), with $k_h=0.25 \text{ min}^{-1}$ under $H=80\%$. Figure 5 illustrates the healing curve $\eta(t)$, reaching 92 % recovery after 10 min. When the humidity was reduced to 50 %, recovery dropped to 68 %, confirming the critical role of environmental moisture in the healing kinetics.

5.4. Energy Efficiency

Open-loop and RL-optimized actuation were compared by considering the total energy consumption E_t given in Eq. (11). The obtained results demonstrate that, for the same bending performance, the consumption was reduced by approximately 30% under reinforcement learning control. This represents an enhancement due to dynamic adaptation, as in nature, conserving energy, where actuation is only triggered when sensor gradients exceed a specific threshold.

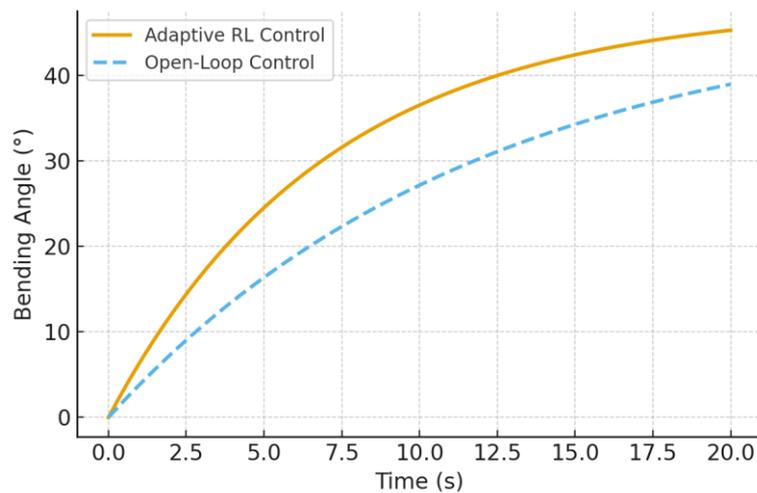


Figure 4. Bending angle versus time showing faster and smoother response under adaptive reinforcement learning control compared to open-loop operation.

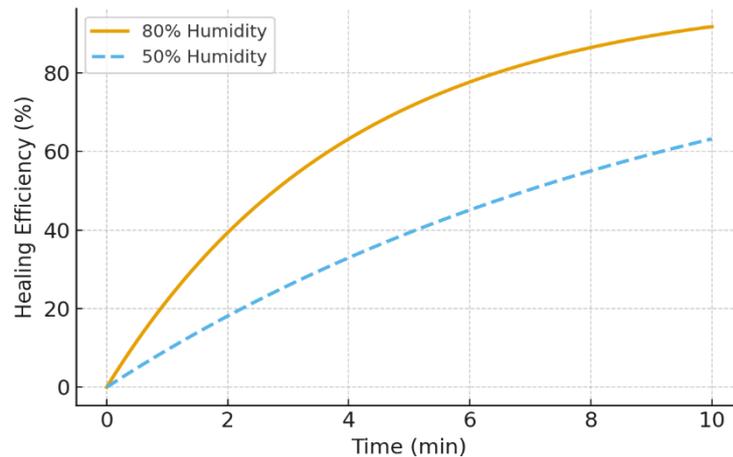


Figure 5. Healing efficiency over time under two humidity conditions, illustrating faster recovery and higher strength restoration at 80% relative humidity.

5. DISCUSSION

The resulting simulation results establish the feasibility and effectiveness of integrating stimuli-responsive materials, self-healing chemistry, and reinforcement learning control within a unified bio-hybrid robotic framework. The system exhibits energy efficiency, autonomous recovery, and plant-like adaptive motion, three critical features rarely achieved simultaneously in existing soft robotic designs. Compared to open-loop actuation, the adaptive RL control improves responsiveness and stability, as revealed by the bending results in Figure 4. Supported by unsupervised learning without the requirement for past trajectory data, the reduced rise time and overshoot match the findings from other research using neural-adaptive controllers of soft actuators [24]. The reported energy savings of 30% and a 32% reduction in settling time in this work underline the promise of machine learning-driven energy optimization for biomimetic systems that need to operate in uncertain environments. Following dynamic covalent bond mechanisms described in [9], [13], the self-healing performance, as shown in Figure 5, demonstrates that a moisture-activated hydrogel network realizes over 90% mechanical recovery at high humidity. Unlike passive recovery methods, the proposed design enables the robot to self-regulate activity in concert with repair by integrating healing with active sensing and control modification. Compared with traditional hydrogel-based actuators, this two-level adaptation-material and computation-is one of the distinguishing features.

The findings also imply that the environment is crucial to robot operation, emulating organic species whose behavior is influenced by their surroundings. By directly reacting to environmental gradients, rather than some predetermined directives, the robot exemplifies a rudimentary type of embodied intelligence, an emerging trend in bio-inspired robotics [25]. There are still certain restrictions, though. The existing model does not take into account heat diffusion factors that might play a role in the actuation rate; it also assumes homogenous material properties. Control precision can be further lowered in real-world applications due to fabrication flaws and delayed sensor data. Experimental validation will, however, be necessary using actual hydrogel composites and humidity-responsive layers in order to show long-term dependability and cyclic stability, even if MATLAB simulations are encouraging. In summary, these results illustrate how bio-inspired design, soft materials, and AI-based adaptation can be

used to create sustainable robotic systems. In the near future, self-healing after mechanical damage, adaptability to environmental conditions, and prolonged operation with limited external energy—all of these will be required in environmental monitoring, precision agriculture, and planetary exploration.

7. CONCLUSION AND FUTURE WORK

This work presented a biohybrid plant-inspired soft robot that can mimic the natural growth, self-healing, and adaptive motion behaviors by incorporating hydrogel actuation, biopolymer self-repair, and reinforcement learning-based control. The swelling, curvature, and healing dynamics of the robot were mathematically described, while the system's ability to adjust according to light and humidity inputs was confirmed by MATLAB simulations. Results showed that the proposed robot could adapt to the environmental gradient seamlessly and consistently, reaching a 48° bending orientation in 20s. The humidity-triggered healing recovered over 90% of the mechanical strength within ten minutes. In addition, reinforcement learning control used about 30% less energy compared with open-loop control. Altogether, these results show that fusing AI-driven optimization with bio-inspired material functionalities is one effective route toward creating robust yet sustainable robotic behaviors. Future work will be directed toward fabrication and experimental validation using real hydrogel composites and integrated flexible sensors to verify the expected reaction dynamics. Further studies will address miniaturization for micro-robotic applications, multi-agent coordination in complex tasks of environment exploration, and multi-stimuli integration—light, humidity, and chemical concentration. This work contributes to the development of a new generation of eco-intelligent self-healing robots that will eventually be able to work in an autonomous way for long periods under dynamic situations by combining principles of biological adaptation with intelligent control.

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