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Design and Implementation of a Concrete Carbon-Sequestration Curing Robot Based on an Elephant-Trunk-Inspired Bionic Arm

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Abstract: Concrete curing is vital for building strength and durability. Traditional methods, however, face issues like unstable quality, high carbon footprints, and resource waste. This paper introduces a robot using an elephant-trunk-inspired arm for carbon-sequestering concrete curing. The system merges biomechanics with electromechanical control, employing a cable-driven soft continuum structure with a "cable traction + flexible backbone" setup. This allows for agile, multi-directional motion and precise spraying across various mediums. Additionally, a multidimensional fuzzy control model enables collaborative curing and carbon sequestration. By tracking real-time environmental data like temperature and humidity, it optimizes spraying to boost concrete hydration and CO_2 absorption. Experimental data reveals that the newly designed robot markedly enhances curing uniformity. When pitted against conventional curing techniques, it slashes water use by about 30% and electricity consumption by 40%. Moreover, it boosts CO_2 sequestration per square meter of concrete by 25%, cutting costs and environmental harm, and aiding green construction.

Keywords: Concrete Curing; Bionic Robotic Arm; Carbon Sequestration; Fuzzy Control; Intelligent Robot.

1. Introduction

Concrete curing is crucial for building strength and durability over time. Yet, traditional methods heavily depend on manual know-how and extensive oversight, frequently leading to inconsistent curing and wasteful use of water and energy. Data from China's housing ministry reveals that almost 35% of concrete flaws stem from incorrect curing practices. [5][6]

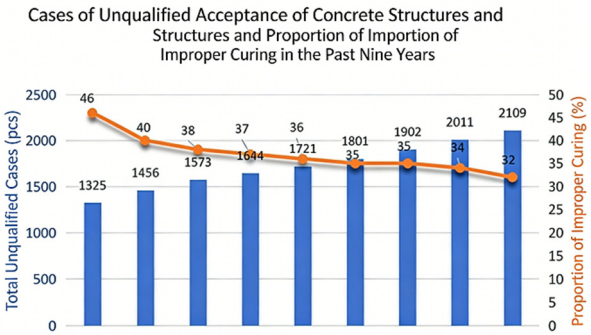


Figure 1. Statistics of Unqualified Concrete Structure Cases and Proportion of Improper Curing in Recent Nine Years

As China advances its "dual-carbon" goals and green building tech surges, the construction sector needs smart gear for top-notch curing and carbon footprint reduction. [1][4]

In recent years, intelligent construction technologies and Internet of Things (IoT) systems have been widely applied in engineering fields. However, most existing studies focus only on environmental monitoring or automated spraying systems, lacking a comprehensive solution that integrates curing quality control with carbon sequestration mechanisms. [5][6][7] In addition, traditional rigid robotic manipulators have limited flexibility in complex construction environments, making it difficult to achieve full coverage of large concrete surfaces.

To tackle existing challenges, our study introduces an intelligent curing robot with an elephant-trunk-inspired soft arm. By merging bionic design, multimodal sensing, and smart algorithms, it enables precise, low-carbon curing, offering an efficient modern construction solution.

2. System Design and Working Principle

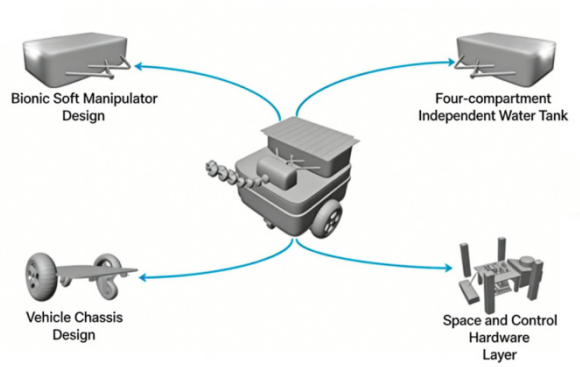


Figure 2. Overall System Design of the Concrete Carbon-Sequestration Curing Robot

(1) Design of Cable-Driven Soft Robotic Arm

The core actuator of the proposed system is a soft robotic arm designed based on the biomechanical characteristics of an elephant trunk.

The arm's flexible backbone is made up of multiple 3D-printed modular plates. Four traction cables, spaced 90° apart around it, mimic the muscle bundles found in an elephant's trunk.

Servo motors adjust cable tension to flex the backbone, enabling the robotic arm to pitch and bend freely. This streamlined cable-driven approach cuts mechanical complexity and boosts adaptability in confined construction

sites

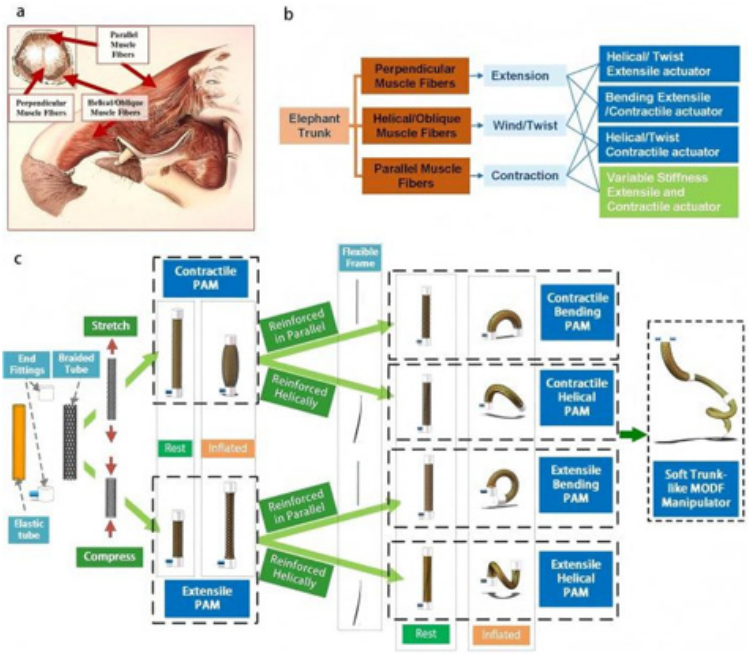


Figure 3. Bionic Design Principle of Elephant Trunk Muscle Fibers and Corresponding PAM Actuator Configurations

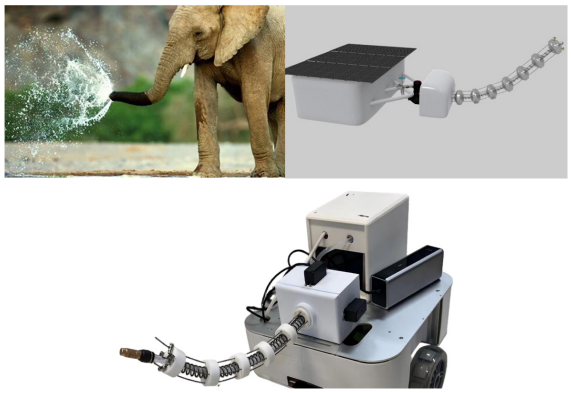


Figure 4. Prototype of the Elephant-Trunk-Inspired Soft Bionic Manipulator

Moreover, the robot's end effector features a four-tank multi-channel spraying system, storing water, curing agents, solidification solutions, and carbon sequestration promoters separately. A multi-way valve and high-pressure pump allow swift media switching, ensuring continuous, efficient curing.

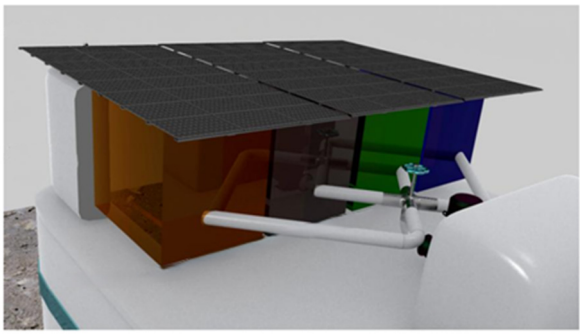


Figure 5. Schematic of Multi-Medium Spraying System with Four Independent Liquid Tanks

(2) Intelligent Curing-Carbon Sequestration Synergy

The proposed system establishes an integrated mechanism combining concrete hydration and CO_2 mineralization.

By keeping concrete surfaces at 20–30°C and over 95% relative humidity, the system boosts cement hydration, yielding alkaline products like calcium hydroxide ($Ca(OH)_2$).

Subsequently, carbon dioxide in the atmosphere diffuses into the concrete matrix and reacts with $Ca(OH)_2$ to generate stable calcium carbonate ($CaCO_3$), thereby achieving permanent carbon sequestration. [4]

The hydration degree α is affected by temperature T, relative humidity RH, and curing time t, which can be expressed as:

$$\alpha(t,T,RH) = \alpha_u[1 - exp(-k(T,RH)t)]$$

where $\alpha_u$represents the ultimate hydration degree.

Through real-time monitoring of environmental parameters, the robot dynamically adjusts spraying intensity to maintain optimal curing conditions.

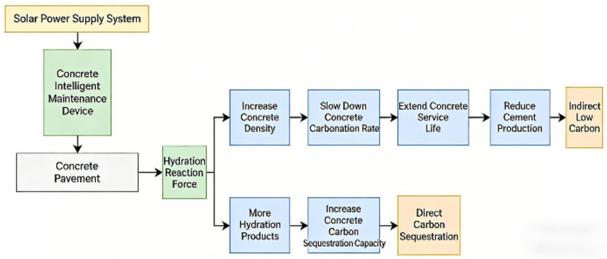


Figure 6. Mechanism of Concrete Hydration and CO_2 Mineralization for Carbon Sequestration

(3) Multidimensional Fuzzy Control Decision Model

Considering the nonlinear and time-varying characteristics of construction environments, a three-dimensional fuzzy control strategy is developed.

The system gathers environmental data like temperature, humidity, and wind speed, then computes moisture evaporation rate to assess curing. These variables are normalized and mapped into fuzzy sets via triangular functions.E

A rule base with 75 fuzzy rules (5×5×3) is set up, using the

Mamdani method with MAX–MIN composition to find the best spraying flow. The centroid method then defuzzifies to create precise control commands.

This closed-loop control mechanism effectively improves system stability and responsiveness compared with traditional threshold-based control methods.

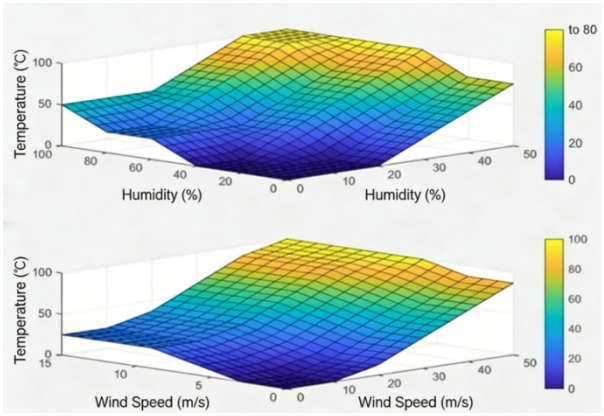


Figure 7. Membership Functions of Temperature, Humidity and Wind Speed in the Fuzzy Control Model

(4) Sensor Fusion Navigation and 3D Reconstruction

To achieve autonomous operation, the robot integrates multiple sensors including LiDAR, depth cameras, and ultrasonic sensors.

An enhanced multi-sensor SLAM algorithm uses an improved VG-PN-ICP point cloud registration method. It employs PointNet++ to extract local geometric features, boosting robustness in low-texture, dusty, or cracked environments.

Using the high-precision map, the system plans global paths and employs the Dynamic Window Approach for local obstacle avoidance, ensuring stable navigation even on wet, muddy construction sites.

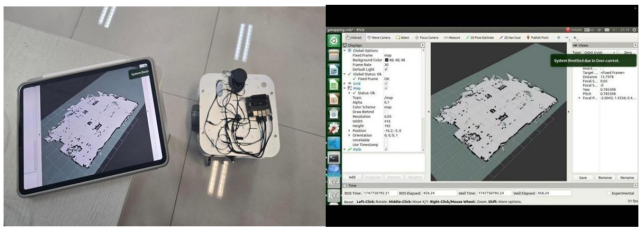


Figure 8. 3D Reconstruction and Point Cloud Map of Concrete Surface Based on Multi-Sensor SLAM

3. System Implementation

(1) Hardware Platform

The robotic platform includes an omnidirectional chassis, an NUC-based upper computer, STM32 controller, and a bionic arm. The chassis, with a two-wheel differential drive in an IP67 shell, handles tough construction sites. Its power system uses lightweight solar panels with an MPPT controller for clean energy. The modular design simplifies maintenance and transport.

(2) Carbon and Energy Evaluation Model

Based on the hydration reaction mechanism of concrete, a quantitative model for CO_2 mineralization and sequestration is established.[4] The amount of mineralized CO_2, denoted as Q_{CO_2}, mainly depends on the hydration degree α, the concrete volume V_c, and environmental reaction kinetic parameters. The model can be expressed as:

$$Q_{CO_2} = (\alpha \cdot V_c \cdot \rho_c \cdot C_{CaO} \cdot \frac{M_{CO_2}}{M_{CaO}} + C_{C-S-H} \cdot \eta) \cdot \int_0^t e^{-E_a/(RT(\tau))}\, d\tau$$

where $\rho_c$represents the density of concrete, C_{CaO}denotes the calcium oxide content (assumed to be 65%), and Mrepresents the molar mass of the corresponding substances. C_{C-S-H} indicates the amount of calcium–silicate–hydrate generated during the hydration process, while η is the carbonation reaction efficiency coefficient. E_a denotes the activation energy of the carbonation reaction (42 kJ/mol), $R$is the universal gas constant, and T represents the absolute temperature. By continuously monitoring environmental parameters such as temperature, humidity, and wind speed during the curing process, the system dynamically adjusts the reaction rate constant, enabling accurate estimation of the CO_2 sequestration capacity per unit volume of concrete.

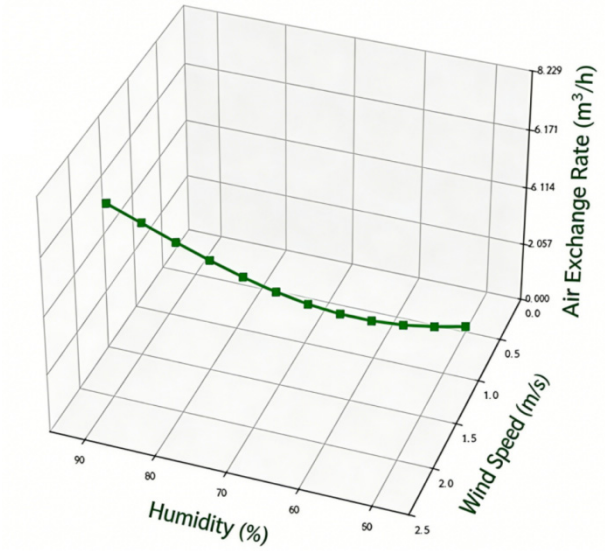


Figure 9. Relationship between Wind Speed and CO_2 Sequestration Efficiency of Concrete

To assess the system's environmental and economic impacts, a four-dimensional model is created, considering carbon sequestration, water savings, energy efficiency, and material improvements. The overall evaluation index is:

$$E_{total} = \beta_1 E_{water} + \beta_2 E_{energy} + \beta_3 E_{material} + \beta_4 Q_{CO_2}$$

where E_{water}, E_{energy}, and $E_{material}$represent the water-saving rate, energy substitution efficiency, and material strength improvement, respectively. The weighting coefficients $\beta$are determined using the Analytic Hierarchy Process (AHP). Considering that direct carbon sequestration is the primary contribution to emission reduction, the weight of the carbon sequestration index is set as $\beta_4 = 0.40$. Since water conservation and energy saving also play significant roles in sustainable construction, their weights are set as $\beta_1 = 0.25$and $\beta_2 = 0.25$, respectively. In addition, material optimization indirectly reduces life-cycle carbon emissions, and thus the corresponding weight is assigned as $\beta_3 = 0.10$.

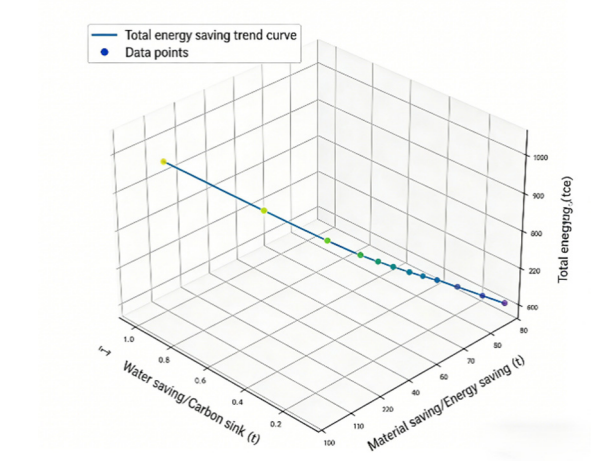


Figure 10. Trend Curves of Total Water Saving, Energy Saving and Carbon Sequestration

To enable real-time monitoring and smart decisions, a data management framework is introduced. The backend uses a MySQL-based distributed database to handle high-frequency sensor data,3D maps, and curing metrics. The front end, built with ROS and Qt, offers real-time monitoring, remote control, and anomaly alerts. By integrating sensor data, intelligent algorithms, and execution control, the system creates a closed-loop workflow from perception to decision-making and execution, with data traceability. This ensures clear visualization and dependable decision support for on-site operation and maintenance.



Figure 11. Human–Machine Interaction Interface of the Intelligent Concrete Curing System

4. Experimental Results and Analysis

Field experiments were conducted in a real construction environment to evaluate the performance of the proposed robot.

First, curing quality improved notably. Compared to manual methods, concrete surface humidity uniformity rose by about 40%, and structural defect rates dropped from 35% to under 5%.[5][7]

Second, the system delivered significant resource savings. Intelligent spraying and solar power cut water use by 30% and electricity by 40%, replacing nearly 80% of manual tasks.

Third, the carbon sequestration capacity of the concrete was enhanced. By optimizing hydration conditions, the CO_2 sequestration per square meter increased by approximately 25%. [4]

Lastly, the system boosted operational efficiency significantly. A single robot can cure over 500 m^2 of concrete daily, improving coverage efficiency by 80% compared to manual methods.

5. Conclusion

This paper introduces a concrete carbon-sequestration curing robot with an elephant-trunk-inspired soft arm, combining bionic mechanical design, intelligent fuzzy control, and multi-sensor navigation.

Tests show the system boosts curing quality while cutting water, energy use, and carbon emissions, offering an effective smart solution for sustainable, low-carbon construction.

Future work will focus on further optimizing the control algorithms and validating the system in large-scale construction scenarios.

Acknowledgments

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