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Dynamic Response and Low-carbon Coordination Mechanism of Bionic Building Epidermis Driven by Group Intelligence

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Abstract: The bionic building epidermis driven by group intelligence simulates the synergistic mechanism of biological group and combines the intelligent algorithm with the principle of biological community to form an innovative system of dynamic response and low carbon synergy. This system, with distributed decision-making framework as the core, through the sensor network real-time sensing environmental parameters (light, temperature and humidity, CO2 concentration, etc.), using the ant colony algorithm (ACO), particle swarm optimization (PSO) group intelligent algorithm to realize the epidermis unit organization coordination, dynamic adjusting shading, ventilation, power generation, and other functions, significantly improves energy efficiency and carbon sink capacity. Typical cases show that this kind of epidermis can reduce building energy consumption by 35-60%, and achieve annual carbon sequestration by 5-18 kg/m². At the same time, resource cycle and carbon negative operation are realized through material regeneration (such as self-repair biological concrete) and bio-mechanical hybrid system (microalgae-photovoltaic symbiosis). Despite the challenges of stability, cost, and standardization, the "building as an ecosystem" paradigm provides a programmable and scalable technological path for global carbon-neutral goals.

Key words: group intelligence; bionic building skin; dynamic response; low-carbon synergy

1. The Development Status of Bionic Building Epidermis Driven by Group Intelligence

The construction industry is one of the core areas of global energy consumption and carbon emission. According to the statistics of the United Nations Environment Programme, building operating energy consumption accounts for 36% of the global total energy consumption, while carbon emission accounts for as much as 39%. As a static maintenance structure, the skin of traditional buildings is difficult to cope with various challenges such as climate change and extreme weather. In this context, the dynamic and intelligent building skin becomes the key to solve the energy consumption.

In recent years, with the intersection and integration of artificial intelligence material science and bionics technology, the skin of bionic architecture driven by group intelligence has gradually become a research hotspot in the field of building intelligence. By mimicking the synergistic mechanisms of natural biological groups, it endows the architectural epidermis with dynamic response to adaptive and distributed decision-making capabilities. It also provides an innovative reform plan for the building energy-saving environment interaction and space experience. The core of group intelligent bionic building epidermis lies in the combination of distributed autonomous system and bionic structure design, and the behavior simulation of biological groups, such as termite nest, to adjust the nest ventilation structure through pheromone transmission between individuals. Fish group obstacle avoidance realizes group obstacle avoidance through local perception and dynamic path planning. Plant stomatal opening and closing is a distributed response network based on environmental stimuli. At present, the group intelligent bionic building skin has been applied in many fields, and has achieved breakthrough development. For example, the Technical University of Munich in Germany adopts a honeycomb modular unit, which adjusts the opening and closing angle through the group algorithm.[1] Through dynamic shading and photothermal adjustment, the energy consumption of air conditioning can be reduced by about 30% in summer. Through research, dynamic game theory and complex system science can be further introduced in the group intelligence-driven bionic epidermis to build a closed-loop mechanism of perception-decision-response. The distributed decision model can eliminate the single-point failure risk of the centralized control system and realize the globally optimized nonlinear response through local interaction.

2. Dynamic Response Path of Epidermis Development of Bionic Architecture

2.1 Material-driven adaptive response mechanism

The bionic building epidermis demonstrates a dynamic response to the breakthrough development of its core, which depends on intelligent materials. It directly senses environmental stimuli and triggers deformation formation through physical and chemical characteristics, without the need for passive response of external energy records. At present, the application of dynamic response has been carried out in many fields, and corresponding results have been achieved. The water-responsive lignin composite developed by Harvard University in the United States automatically selects or develops the opening and closing mechanism of pine cone scales through the humidity-sensitive characteristics of molecular weight. The material is applied to the skin of buildings in Dubai office buildings to achieve humidity over 6%, increase the deployment rate of 10 units by 80% and increase the natural ventilation rate by 45%. The SMA grid epidermis developed by the German Institute automatically bends when the temperature exceeds 35 degrees, forming such a structure with a response time of less than 30 seconds.[2]

The piezoelectric ceramic epidermis developed by Delft University of Technology produces the opening and closing of the microcurrent driving unit through partial voltage vibration to realize zero-energy consumption dynamic regulation. For every 200 W/m^2 increase of the ultraviolet intensity of the photosensitive polymer film, the light transmittance will be reduced by 40%, which can reduce the building refrigeration composite by 22%. Such materials have the autonomous response ability of life-like epidermis, but they need to solve multiple technical problems such as materials, durability and multi-parameters and interference.

2.2 Algorithm-driven group intelligent regulation network

The distributed decision system, based on the group intelligent algorithm, the multi-objective optimization and self-organization coordination ability of the building epidermis, breaks the limitations of the traditional central control system. The project by the Institute of Advanced Architecture in Catalonia, Spain, has 3000 hexagonal shading units. Each unit obtains data through a local light sensor and uses the algorithm to dynamically calculate the optimum. Compared with the traditional timing control, the use of the system can ensure that the building energy consumption is reduced by more than 30% in summer, and avoid excessive shading, resulting in insufficient indoor lighting and other problems. The photovoltaic skin of the University of Nottingham adopts the algorithm to adjust the photovoltaic angle, so that the volatility of the power generation efficiency can be reduced from 25% to about 8% in the cloud change scenario.

2.3 Bionic integration of multi-level systems

Cross-scale collaborative design from microscopic materials to macroscopic buildings is a systematic guarantee for the bionic epidermis to achieve efficient and dynamic response, and it also includes the deep coupling between structural energy and biological system. Tongji University of China proposed a cell robot skin, where each module integrates sensors, drivers and micro-photovoltaic cells to achieve plug and play through a magnetic suction interface. This design has been applied in the experiment, and the module failure rate is 90% lower than that of the traditional system, and the local unit replacement and upgrade is supported. A project by the Swiss Federal Institute of Technology in Zurich integrates an algae bioreactor and flexible photovoltaic panels into building epidermis to absorb carbon dioxide through daytime photosynthesis, while utilizing biomass energy to power ventilation systems and achieve over 40% energy self-sufficiency for the building. The project at the University of California, Berkeley embeds live moss into the skin, uses plant transpiration to regulate humidity, and adjusts irrigation frequency by monitoring moss growth dynamics through strain sensors.[3]

3. Low-carbon Collaborative Results of Bionic Building Epidermis Driven by Group Intelligence

3.1 Energy efficiency optimization is obvious

In terms of energy efficiency optimization, the group intelligence-driven bionic building epidermis shows a revolutionary breakthrough. The core lies in the deep integration of the bionic collaborative decision-making mechanism and the dynamic response technology, which breaks through the traditional energy management mode of static homogenization of building epidermis. This approach treats the building epidermis as a complex system composed of numerous intelligent units. By simulating the biological collective behaviors, for example, the wind group cooperation and participation in local interaction rules, the optimal global energy consumption can be achieved. At the same time, the group intelligence algorithms, for example, the particle swarm optimization, through dynamic game learning and multi-objective optimization, establish a dynamic balance in shading, lighting, ventilation, and power generation. Unlike traditional centralized control systems, which rely on preset machine threshold for one-way control, the group vibration system can conduct unit collaborative calculation by implementing environment sensing, thus improving the closed-loop logic of the nonlinear response, and transverting the architectural epidermis into a "breathing skin". Here, each unit is the terminal of the execution and also the node of decision-making. Decentralized decision networks emerge via localized information sharing, fostering adaptability and resilience.[4]

Group intelligent algorithm, by optimizing the spatiotemporal layout and operational development of wind power distributed energy units, can significantly improve clean energy utilization. For example, when fast-moving clouds cause rapid fluctuations in light intensity, the algorithm can recalculate the global optimal configuration within 20 seconds. Compared to fixed photovoltaic systems, this approach enhances power generation efficiency while reducing grid dependency and carbon emissions. Furthermore, based on the principle of bionic fluid mechanics and the group intelligent epidermis regulation system, the seamless connection between natural ventilation and mechanical refrigeration can be realized by adjusting the stomatal opening and closing freely.

3.2 Material regeneration and system self-consistency

Group intelligence-driven bionic building epidermis has achieved a significant breakthrough in the field of material regeneration and system self-consistency. This advancement also marks the transformation of architecture from linear consumption to a metabolic cycle mode, based on the deep integration of biomimetic metabolic cycle theory and distributed resource management model. By further incorporating the material and energy transformation mechanism of natural organisms, we can develop innovative building materials. At the same time, the path fusion of repair and degradation is carried out in many aspects of the regeneration cycle, and dynamic optimization and regulation of the material life cycle are carried out through the group intelligent algorithm, effectively improving the epidermis loss of traditional buildings in resource allocation, minimizing reliance on manual maintenance or overall replacement.[5]

Bionic epidermis can endow material living organisms with dynamic repair capabilities through multi-level collaborative mechanisms such as embedded perception, healing feedback, and regeneration scheduling. For example, the resource allocation model based on the group algorithm can accurately deliver the repair materials to the damage area, avoiding the overall natural waste of learning techniques. Through reinforcement, historical data can be utilized for training to predict material aging trends, ensuring that the material life cycle loss rate is reduced by more than 50%. Through the biomimetic structure and the intelligent algorithm, the synergistic epidermis system can independently identify the damage and punish the repair mechanism.

3.3 Bio-mechanical hybrid system is relatively mature

The group intelligence-driven epidermis of biomechanical hybrid biomimetic buildings achieves the organic symbiosis of living systems and artificial machinery, through the integration of the principles of synthetic biology ecology and distributed intelligent control. This technology has also become one of the widely applied fields with high maturity in the current low-carbon technologies. By using ecology as complementary theory and biomechanical interface synergy model, it can further simulate the energy and material exchange between species in natural ecosystems to divide biological components into natural biological and mechanical systems.

4. Conclusion

Through the deep integration of bionic collaborative decision-making, dynamic response optimization and the biological and mechanical system, the group intelligence-driven bionic building skin constructs the interactive paradigm between architecture and environment, and realizes the qualitative change from "energy consumption" to "carbon-negative life".

Despite facing the challenges from biological active maintenance and interdisciplinary standards, the technology, through innovations, such as synthetic biology and neural form computing, is promoting buildings to become urban carbon sink network nodes, providing implementation and ecological inclusive solutions for the global carbon neutral target, marking the human towards the era of "intelligent buildings coexisting with nature".

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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