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Design and Fabrication of AI-Driven Kinetic Facades with Soft Robotics for Optimized Building Energy Performance

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Abstract : This paper explores a kinetic building facade designed for optimal energy capture and architectural expression. The system integrates photovoltaic panels with soft robotic actuators for precise solar tracking, resulting in enhanced electricity generation compared to static facades. Driven by the growing interest in dynamic building envelopes, the exploration of facade systems is necessitated. Increased energy generation and regulation of energy flow within buildings are potential benefits offered by integrating photovoltaic (PV) panels as kinetic elements. However, incorporating these technologies into mainstream architecture presents challenges due to the complexity of coordinating multiple systems. To address this, the design leverages soft robotic actuators, known for their compliance, resilience, and ease of integration. Additionally, the project investigates the potential for employing Large Language Models (LLMs) to streamline the design process. The research methodology involved design development, material selection, component fabrication, and system assembly. Grasshopper (GH) was employed within the digital design environment for parametric modeling and scripting logic, and an LLM was experimented with to generate Python code for the creation of a random surface with user-defined parameters. Various techniques, including casting, 3D printing, and laser cutting, were utilized to fabricate the physical components. A modular assembly approach was adopted to facilitate installation and maintenance. A case study focusing on the application of this facade system to an existing library building at Politecnico di Milano is presented. The system is divided into sub-frames to optimize solar exposure while maintaining a visually appealing aesthetic. Preliminary structural analyses were conducted using Karamba3D to assess deflection behavior and axial loads within the cable net structure. Additionally, Finite Element (FE) simulations were performed in Abaqus to evaluate the mechanical response of the soft robotic actuators under pneumatic pressure. To validate the design, a physical prototype was created using a mold adapted for a 3D printer's limitations. Casting Silicone Rubber Sil 15 was used for its flexibility and durability. The 3D-printed mold components were assembled, filled with the silicone mixture, and cured. After demolding, nodes and cables were 3D-printed and connected to form the structure, demonstrating the feasibility of the design. This work demonstrates the potential of soft robotics and Artificial Intelligence (AI) for advancements in sustainable building design and construction. The project successfully integrates these technologies to create a dynamic facade system that optimizes energy generation and architectural expression. While limitations exist, this approach paves the way for future advancements in energy-efficient facade design. Continued research efforts will focus on cost reduction, improved system performance, and broader applicability.

Keywords : artificial intelligence, energy efficiency, kinetic photovoltaics, pneumatic control, soft robotics, sustainable building
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