SCIENCE ROBOTICS | RESEARCH ARTICLE

ROBOT SWARMS

Architectural swarms for responsive façades and creative expression

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Living architectures, such as beehives and ant bridges, adapt continuously to their environments through self-organization of swarming agents. In contrast, most human-made architecture remains static, unable to respond to changing climates or occupant needs. Despite advances in biomimicry within architecture, architectural systems still lack the self-organizing dynamics found in natural swarms. In this work, we introduce the concept of architectural swarms: systems that integrate swarm intelligence and robotics into modular architectural façades to enable responsiveness to environmental conditions and human preferences. We present the Swarm Garden, a proof of concept composed of robotic modules called SGbots. Each SGbot features buckling-sheet actuation, sensing, computation, and wireless communication. SGbots can be networked into reconfigurable spatial systems that exhibit collective behavior, forming a testbed for exploring architectural swarm applications. We demonstrate two application case studies. The first explores adaptive shading using self-organization, where SGbots respond to sunlight using a swarm controller based on opinion dynamics. In a 16-SGbot deployment on an office window, the system adapted effectively to sunlight, showing robustness to sensor failures and different climates. Simulations demonstrated scalability and tunability in larger spaces. The second study explores creative expression in interior design, with 36 SGbots responding to human interaction during a public exhibition, including a live dance performance mediated by a wearable device. Results show that the system was engaging and visually compelling, with 96% positive attendee sentiments. The Swarm Garden exemplifies how architectural swarms can transform the built environment, enabling "living-like" architecture for functional and creative applications.

INTRODUCTION

Living architectures, such as plants, beehives, and army ant bridges, are constantly evolving in response to their environments with immediate and long-term adaptations. These adaptations emerge from self-organization, whereby individual agents (for example, cells and insects) interact locally with each other, sense their local environment, and, through networked interactions, create globally complex responses (*1*). Plants optimize their shape to sunlight and nutrients through mechanical and signaling interactions of individual cells that sense external stimuli (*2*). Beehives continually adapt the distribution of brood versus honey cells through self-organized actions of individual bees (*1*). Army ants build living bridges out of their own interlinked bodies that adapt in real time to traffic and terrain changes (*3*). These natural, living architectural systems have inspired the field of swarm intelligence, which explores how natural agents self-organize to create complex collective behaviors and how such algorithms can be applied to the design of artificial systems (*4*).

In contrast with these living architectures, human-designed architectures are for the most part static, designed with rigid elements that remain fixed even as the environment and occupants' needs change (*5*). This inflexibility hinders the ability to adapt to different occupants' requirements or daily, seasonal, and yearly climate variations. However, if human architectures were designed to be dynamic, or "living-like," then they could incorporate many interacting agents that self-organize to respond to daily to seasonal climate variations and different occupant requirements and even enhance health and well-being. Such agents could leverage swarm intelligence to create spaces that evolve over time.

Currently, the application of swarm intelligence in architecture has been limited to the design process to address "task fitness" challenges. The architectural design process is complex, involving multi-objective optimization. Its task fitness refers to how well a physical design balances often-competing requirements such as layout, aesthetics, structural and environmental performance, and material efficiency. Traditional architectural design processes rely heavily on tacit knowledge and human expertise, limiting the exploration of diverse solutions. Swarm intelligence algorithms have been successfully applied to a multitude of complex optimization scenarios (*6*, *7*), enabling the exploration of large complex design solution spaces and providing solutions that are not apparent in the traditional design process. For example, swarm algorithms inspired by plants, insects, and bird flocks have been applied to creative structural design and complex energy optimization scenarios (*6*, *8*, *9*). However, unlike the swarm systems that inspire them, these architectural systems are typically static.

Adaptive and dynamic architecture has been explored in the design of façades. The work exploring biohybrid techniques in architecture (*10*) aims to create "living buildings" that integrate biological elements. Examples include the integration of algae panels for shading and energy generation (*11*) and the use of robotic modules to guide plants' growth to create a structure (*12*). These systems are limited to environments that can sustain living materials and do not integrate human interaction. However, they inspire the design of façades that mimic natural beauty while also being functional. Most

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adaptive façade systems typically consist of arrays of mechanical modules that are responsive to external stimuli in a physical environment (*13*). The overarching goal is climate-adaptive building skins that respond to changing conditions or occupant preference—often by shape-morphing—to improve thermal or visual comfort, ventilation, or acoustic properties (*14*–*18*). Modular designs allow for tunability in mixed-use spaces. The mechanical modules are typically based on rigid mechanics of origami or rigid-body motions (*19*–*22*), and famous examples include Al Bahr Towers (Aedas Architects, Abu Dhabi, United Arab Emirates) and Institut du Monde Arabe (Jean Nouvel, Paris, France). These modular façades are often limited by the mechanical complexity and lack of robustness of the individual rigid modules. This has led to the recent exploration of soft modules with continuous deformation, which bring their own challenges in materials and modeling (*13*, *23*). Notable examples include façades composed of 4D-printed hygromorphic bilayer panels (*24*), thermally responsive bimetallic beams and shells for temperature and ventilation control (*5*, *25*), and torsional-compressive buckling driven lamellar shading elements such as the One Ocean pavilion (soma architecture, Yeosu-si, South Korea). These soft façades are often inspired by nature—for example, the shape-change and phototropic motions of plants—and incorporate biomimicry. However, none of these adaptive architectural systems incorporates swarm intelligence. Although modular, they are often rigid, with control that is either completely centralized (hard to scale) or completely decentralized (risking uncoordinated or conflicting actions). They often do not allow programmability to adapt to new environments or to incorporate human interaction. In contrast, swarm robotic modules can deliver globally coherent behavior and enhance robustness against individual errors through redundancy. They also provide programmability and modularity, enabling reuse and adaptation to new tasks, integration of human preferences through human-robot interaction, and deployment in a wide variety of environments. This reusability supports sustainability, which further could be enhanced by reduced costs from mass manufacturing and renewable energy use.

The field of swarm robotics applies concepts from swarm intelligence to the design of physical systems, where many robotic agents cooperate to exhibit complex behaviors that are scalable and robust (*4*). Traditionally, most swarm robots have been developed as mobile ground robots, aerial robots such as quadcopters, or underwater robots. Example applications include inspection, agriculture, and logistics (*26*). In architecture, robots have been applied primarily to the construction process (*27*–*30*), although only a few leveraged swarm intelligence (*30*). There has also been an exploration of self-reconfiguring modular robots for furniture and interior design (*31*, *32*). Swarms specifically designed to interact with humans are uncommon and usually focus on a single application, such as education (*33*, *34*) or art (*35*–*37*). Notable exceptions include systems like MOSAIX (*38*) and Zooids (*39*); MOSAIX uses mobile ground robots to help human groups collaborate, and Zooids uses tabletop mobile robots as a display for social tasks. These systems demonstrate the potential of swarm robotics to move beyond traditional applications and engage directly with humans in diverse, meaningful ways. However, their form is still restricted to wheeled mobile robots. Swarm robots that are integrated into human environments, such as architectural façades, are an emerging physical design space that remain to be explored and represent an exciting direction for swarm and human-robot interaction research.

Here, we introduce the concept of architectural swarms—systems that integrate swarm intelligence and swarm robotics into modular architectural façades to achieve complex environmental and human-centric adaptation through self-organization. Such adaptations could include improving ideal natural light levels and distribution in human spaces, responding to diverse user comfort preferences, and creating visually appealing interior environments (*40*, *41*)—all factors that could contribute to uplifting mental moods and increasing overall occupant well-being (*42*, *43*). It could also enable new forms of creative expression. Architecture has served as a medium of human creativity and expression, with designers weaving aesthetics and culture alongside functionality to communicate with the world (*44*, *45*). In a similar way, robotics has been explored as a medium for creative expression (*46*). Robot swarms have been used to paint (*35*), play music (*47*), and dance (*48*), helping humans convey emotions and ideas beyond purely industrial applications. To this end, we created the Swarm Garden, a proof of concept of architectural swarms, that enables exploration of adaptive shading and creative expression through a reconfigurable swarm of robot modules, called SGbots, which collectively respond to light, motion, and neighboring robots [see Fig. 1 (A to D) and Movie 1]. The system can be configured into large spatial networks that coordinate through programmable nearest-neighbor rules. Each SGbot functions as a façade module whose soft, continuous buckling-based blooming-like actuation achieves complex three-dimensional (3D) shape change using only a single–degree-of-freedom actuator. It offers organic motion with minimal mechanical complexity, replacing complex folded or hinged origami structures that are difficult to manufacture and prone to jamming failures. In our first case study, we show that architectural swarms can perform self-organizing adaptive shading, where an opinion-dynamics controller robustly enables collective adjustment to sunlight in a 16-SGbot real-world window deployment (Fig. 1E), with additional tunability demonstrated in large-scale simulations. In our second case study, we demonstrate the potential of architectural swarms as expressive and interactive media for interior design, supported by a public exhibition where more than 100 participants and a dancer (Fig. 1F) engaged with the Swarm Garden through various interaction modes, including a wearable device. Through these case studies, the Swarm Garden guided the deployment of living-like architectures for functional and aesthetic applications, demonstrating the versatile potential of architectural swarms. It advances adaptive façade design by incorporating swarm intelligence and integrating multiple inputs for dynamic responses and advances swarm robotics by pushing the boundaries of human-centric applications.

RESULTS

This section presents the design of the Swarm Garden and results from real-world deployments for two case studies. Case study 1 investigated the application of the swarm as an adaptive shading façade. Case study 2 investigated the application of the swarm for interior design and creative expression.

The Swarm Garden system design

The Swarm Garden consisted of 40 modular, rearrangeable, robotic agents called SGbots. These robots formed a responsive architectural swarm through an interconnected WiFi network, enabling a shared communication protocol that facilitated collective decision-making among the robots and interaction with other devices in

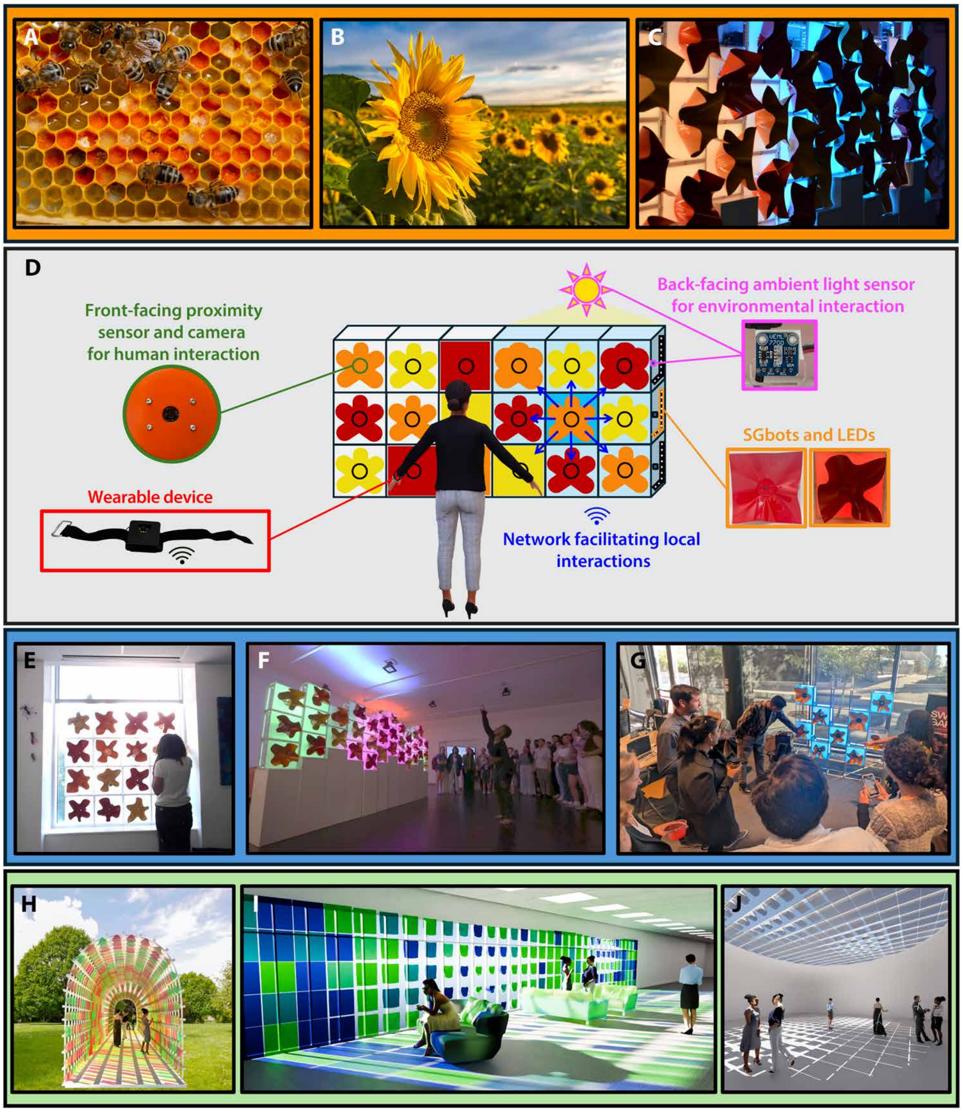

Fig. 1. The Swarm Garden. (**A** and **B**) Bioinspiration from natural living architectures, like beehives and fields of flowers, that constantly respond and adapt to their environments. (**C**) SGbots from the Swarm Garden. (**D**) The various components of the Swarm Garden. (**E**) Sixteen SGbots were deployed on an office window for shading. (**F**) A live dance performance with the Swarm Garden during an exhibition. (**G**) The Swarm Garden exhibited as a swarm of sunflowers. (**H** to **J**) The Swarm Garden envisioned deployed on varied structures (created using Blender).

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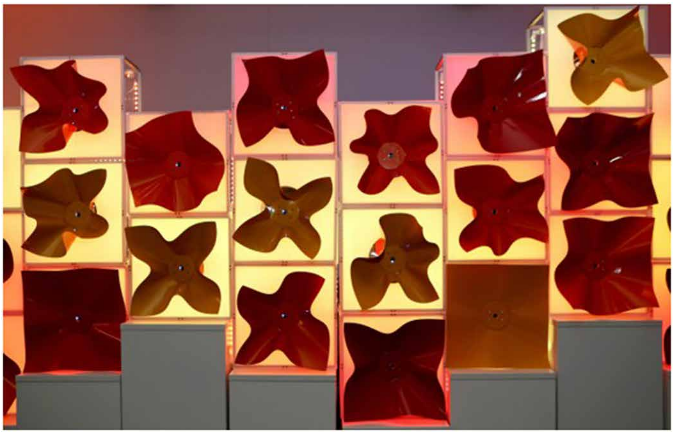
their environment, such as sensors and wearable devices. The Swarm Garden could be configured and deployed in different spatial configurations, as shown in Fig. 1 (E to J). A localization method, detailed in Materials and Methods, allowed the SGbots to identify their nearest neighbors, enabling swarm intelligence algorithms and emergent collective behavior.

Each SGbot was an autonomous robot, capable of sensing, computation, actuation, and communication. It had a back-facing ambient light sensor that allowed it to sense the intensity of light and a front-facing proximity sensor (the "interaction sensor") that allowed it to respond to human interaction (see Fig. 2). The response of each SGbot after sensing the environment and communicating was through "blooming." This process involved pulling a centrally clamped thin plastic sheet, the "plate," through a circular opening, actuated by a simple single–degree-of-freedom mechanism using a threaded rod that retracted and extended the plate. We refer to the process of the sheet buckling (when it is retracted) and then flattening (when it is extended) as blooming. This mechanism was chosen for its high simplicity, reliability, and precision. Other forms of actuation were considered, and we elaborate on their trade-offs in Supplementary Methods. A time-of-flight sensor was positioned near the nut of the threaded rod, acting as an encoder to measure and monitor how far the plate was extended, denoted by "encoding sensor" in Fig. 2A. The plate confinement caused the plate to buckle circumferentially into flower-like patterns of truncated developable cones [see Fig. 2 (B and C)], as first examined by Stein-Montalvo *et al.* (*49*) and further rationalized by Seffen (*50*). The Swarm Garden leveraged the controllable buckling patterns and large deformations exhibited by the confined sheets to enable modular adaptive façade applications. The blooming deformation had a "gentle" appearance and took 10 s to go from fully flattened to fully buckled. Faster actuation speeds were possible, but they required more power, highlighting a trade-off between speed and energy efficiency. To further enable fast dynamic appearance change, light-emitting diode (LED) strips were mounted on the back-side acrylic sheet of the robot. This design feature allowed the robot to change colors (see Fig. 2D), offering ease and flexibility to present multiple looks, especially for artistic and aesthetic purposes. See Fig. 2E for the process of blooming, Materials and Methods for more details on the design of the SGbot, and table S1 for each SGbot's bill of materials.

The Swarm Garden was highly versatile and robust; it was tested in multiple deployments, including an office environment; a public exhibition in the Lewis Center for the Arts, Princeton University, with more than 100 attendees; and robotics conferences in New York City and Detroit. Many collective behaviors were successfully implemented, including classical swarm intelligence algorithms such as gradients and opinion dynamics.

Case study 1: Swarm robots for adaptive façades

The Swarm Garden could be envisioned as a light-adaptive shading façade, where the individual agents sense external light in their spatial region and collaborate to create user-tailored internal illuminances (Fig. 1, H to J). In this case study, we aimed to understand how



Movie 1. Architectural swarms overview video. Introduction to architectural swarms and demonstrations of the Swarm Garden's various applications and deployments.

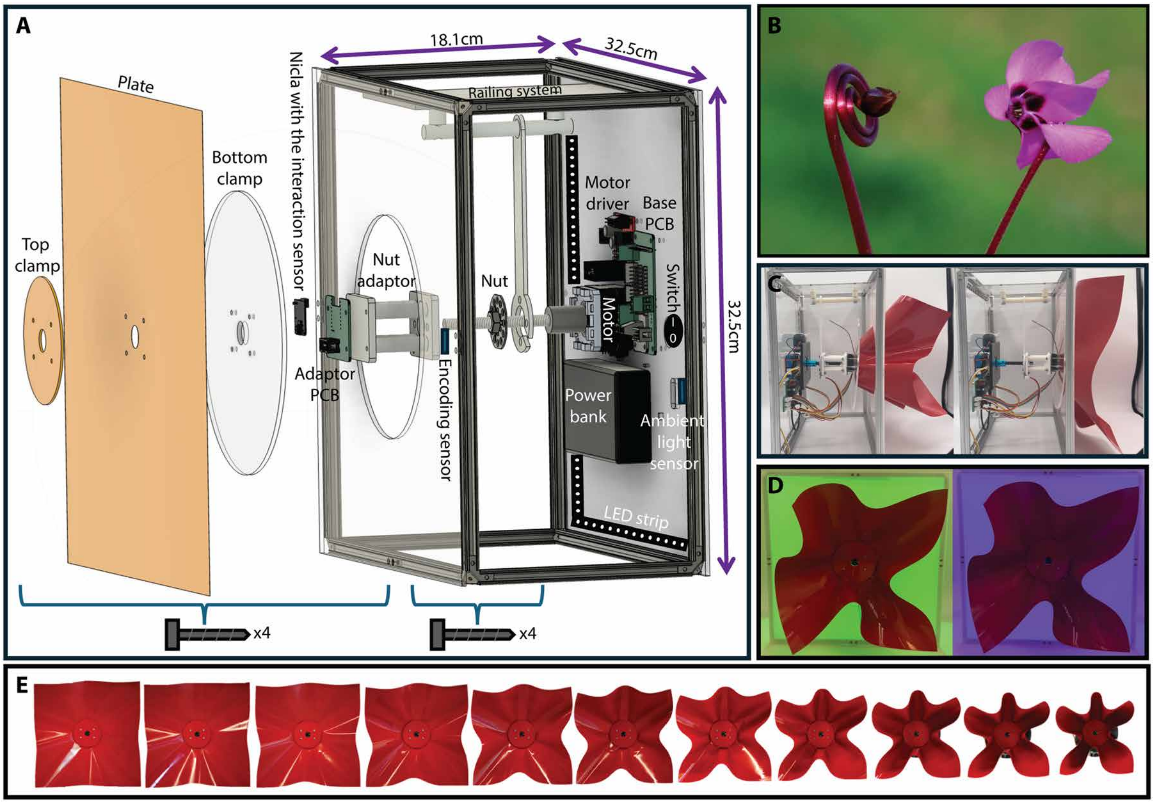


Fig. 2. The SGbot design. (**A**) The components and dimensions of the SGbot robot. (**B**) A natural flower blooming. (**C**) An SGbot blooming. (**D**) Examples showing how frosted acrylic enables light to be diffused across the surface of the acrylic sheet, providing color customization of SGbots. (**E**) The process of blooming; as the plate is pulled through the open ring, the SGbot buckles and contracts.

CREDIT: (B) ISTOCK

self-organization can enable a façade's capacity to respond to changing external lighting and weather conditions, mitigate sensor and communication failures, and integrate user preferences. We studied this with the physical deployment of 16 robots in an office window over an 8-day period, where there was substantial day-to-day weather variation. We enhanced individualistic response by a collective decision-making approach that attempted to maintain a desired internal illuminance and adapt to failures. We also investigated a more complex scenario: a large-scale atrium ceiling swarm using numerical simulations (Rhino3D/Grasshopper). Additional analyses of both the collective decision-making and atrium studies are provided in Supplementary Methods.

Adaptive shading with an individualistic approach

For 3 days, 16 SGbots were placed on an office window (see Fig. 1E), operating continuously for 7 hours each day, from 7:00 to 14:00. The experiments were conducted in mid to late August, a time when the sun typically appeared at the chosen window around 7:15 a.m., intensified by ~9:00 a.m., and disappeared from the window's view by about 11:00 a.m. (obscured by a nearby building). To assess the system's responsiveness to sunlight, we developed a proportional controller that adjusted the SGbot's bloom level (the plate displacement) to the illuminance readings from the ambient light sensor. The aim of the proportional controller was to cause the plate to fully extend, blocking sunlight when it was strong. As the sunlight weakened and the room darkened, the plate gradually buckled to allow more light to pass through. The plate displacement was measured by the encoding sensor placed on the nut adaptor of the threaded rod (see Fig. 2A). The ambient light sensor on the back of the robot was positioned against the window, measuring outdoor illuminance from sunlight. Equation 1 presents the proportional controller used on each SGbot

$$\begin{aligned} &u_i(t) = k_p e(t) + b \\ &\text{where } e(t) = x_i(t) - x_i(t-1) \text{ and } x_i(t) = s_i(t) \end{aligned} \tag{1}$$

$u_i(t)$ was the control output in the form of pulse width modulation signal value given to the motor of SGbot i to buckle or flatten the plate. k_p was a proportional gain. b was a control bias term. $e(t)$ was the error between the normalized desired value of the encoding sensor $x_i(t)$ and the normalized current sensor reading $x_i(t-1)$. To achieve proportionality, the desired value of the encoding sensor, which determined how far the plate was extended (how bloomed the robot was), was set to equal the normalized value of the ambient light sensor $s_i(t)$. More information on illuminance thresholds and the normalization process can be found in Supplementary Methods. In this configuration, each SGbot operated independently, relying solely on its own sensor to react on the basis of sunlight exposure.

As can be seen from Fig. 3A, the robots responded well to sunlight, buckling and flattening proportionally to the amount of ambient light sensed. Movie S1 shows a sped-up video of the experiment. The Pearson correlation coefficient between the time series data throughout the experiment of the encoding sensor values and the ambient light sensor values on that day was $r = 0.98$. Figure 3B shows the results from a cloudy day (movie S2 shows a sped-up video of the experiment), with a Pearson correlation coefficient of $r = 0.95$. The mean, SD, and P value of the correlation coefficients for all 3 days (of which 2 were sunny and 1 was cloudy; see third day results in fig. S1) were, respectively, $\mu = 0.963$, $\sigma = 0.015$, $P < 0.0001$.

The high correlation in the results confirms that the robot's response to illuminance was proportional, even under varying weather conditions. However, in this individualistic approach, robots did not take into account any user preferences for desired indoor illuminance, nor did they cooperate with their neighbors to take advantage of redundancy in case of failures. The next study addressed these issues using swarm intelligence.

Adaptive shading using collective opinion dynamics

We aimed to test whether we could enhance the system's robustness and incorporate a broader range of influencing factors. At the same time, we wanted to maintain the desirable proportional response to sunlight obtained from the previous experiments. Therefore, we developed a mathematical model based on opinion dynamics (*51*) called the Swarm Garden opinion dynamics model (SG_od). Opinion dynamics is a well-known swarm intelligence framework often used to model collective decision-making in natural swarms, such as honey bees (*52*). It can be used to enable agents in a swarm to integrate various factors to make a decision, including input from neighboring agents and environmental cues. Similarly, the SG_od model (Eq. 2) allowed each robot to make decisions on the basis of three terms: its own ambient light sensor readings, those of its neighbors, and the preferred ambient light level in the room. In contrast with linear consensus models like the DeGroot model (*53*), the SG_od model introduced nonlinearity and adaptive weights. The nonlinearity enabled stability by deactivating the model when environmental conditions aligned with user preferences and activating only when adaptation was needed. Adaptive weights supported sensor fusion by adjusting the influence of each term in response to failures and lighting conditions.

We installed an ambient light sensor in the room to measure its illuminance levels (that is, the indoor illuminance). The sensor's data

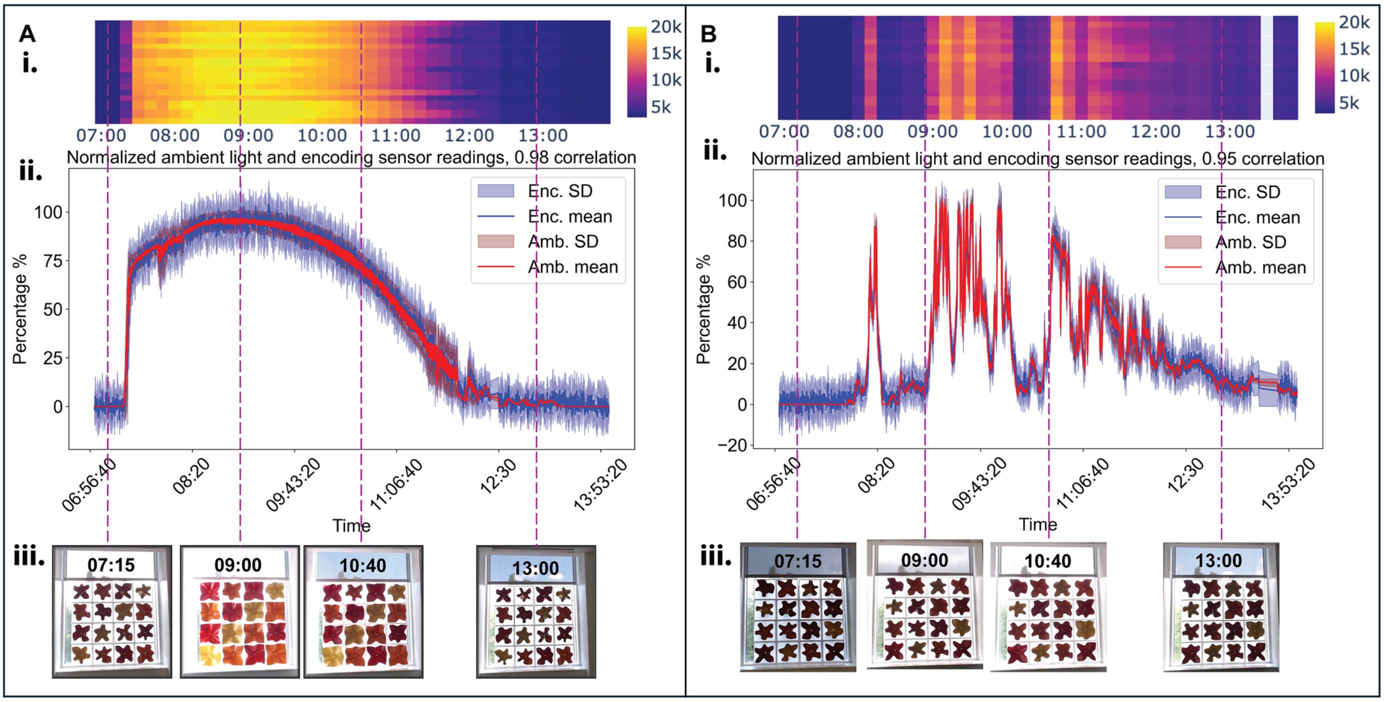


Fig. 3. Adaptive shading experiment results using an individualistic approach run from 7:00 to 14:00 in a real office. (**A**) Results on a sunny day. (i) Heatmap showing the raw illuminance values measured by each SGbot during the experiment. Each row in the heatmap corresponds to 1 of 16 SGbots. (ii) The 10-min running means of the normalized encoding (Enc.) sensor readings, corresponding to plate displacement, are shown as a solid blue line averaged across all 16 robots, with the shaded blue region indicating the SD from the mean across all robots ($n = 16$). The 10-min running means of the normalized ambient (Amb.) light sensor readings are shown as a solid red line averaged across all 16 robots, with the shaded red region indicating the SD from the mean across all robots ($n = 16$). (iii) Images of the window shown in different time stamps. (**B**) (i to iii) Results on a cloudy day running the same experiment.

were then incorporated into the SG_od model as an influencing factor to the overall buckling of SGbots to help regulate the room's lighting on the basis of a user's preference. We assumed the user preference to be at 750 lux, a value that could increase or decrease on the basis of different users. In addition to user preference, we integrated each SGbot's neighbors' opinions into the model as another influencing factor. By doing so, we aimed to incorporate redundancy to mitigate failures or noise arising from individual sensors. We tested the SG_od model for 5 days in a similar setup to the individualistic approach experiments: 16 SGbots, 7 hours each day, from 7:00 to 14:00

$$x_i(t) = \Delta\left(\underbrace{\alpha s_i(t)}_{\text{1st term (own sensor)}} + \underbrace{\beta \sum_{\substack{j=0 \\ j \neq 1}}^{n} \frac{s_j(t)}{n}}_{\text{2nd term (neighbors' sensors)}} + \underbrace{\gamma k_r}_{\text{3rd term (room's sensor)}} \right) - \left((\Delta - 1) \cdot \left(x_i(t-1) \right) \right) \tag{2}$$

and

$$\Delta = \begin{cases} 0 \text{ if} -0.2 < \tanh\left(s_r(t)\right) < 0.2 \quad \left(\text{equivalent to } 650 \text{ lux} < s_r(t) < 850 \text{ lux}\right) \\ 1 \text{ otherwise} \end{cases}$$
$$\gamma = 0.5\tanh\left(s_r(t)\right), \alpha = 0.5(1-\gamma), \beta = 1 - \alpha - \gamma \tag{3}$$

In the SG_od model (Eq. 2), the SGbot *i*'s $x_i(t)$ was influenced by its own sensor, its neighbors' sensors, and the room sensor; the coefficients α, β, and γ were weights to each of those terms (Eq. 3). si (t) was the illuminance value of SGbot *i*'s own ambient light sensor, $s_j(t)$ was the illuminance value of a neighboring SGbot *j*'s ambient light sensor, and *n* was the total number of SGbots in the neighborhood of SGbot *i*. k_r was a constant scaling factor. $s_r(t)$ was the illuminance value of the room's ambient light sensor. All sensor values were normalized.

The △ operator was a nonlinear activation function that determined whether the model activated or not (Eq. 2). If the illuminance in the room was within a preferred user range, in this case chosen to be in a close range to 750 lux, then the model was deactivated, △ = 0, and the robot maintained its status quo [denoted by $xi(t-1)$]. If the room's illuminance started deviating from 750 lux, then the model was activated, △ = 1, to adjust plate displacement; see fig. S2 for a graph of the activation function. The preferred illuminance, 750 lux, could be adjusted by normalizing the input to the hyperbolic tangent function depending on the user's preference. The hyperbolic tangent function was further used with the third term's coefficient, γ, where both were directly proportional (see the third term in Eqs. 2 and 3). Consequently, the room's illuminance had a weight that affected the behavior of the system, especially when the room was too dark or too bright. This was because the more the room's illuminance deviated from 750 lux in either direction, the greater the contribution of the third term. However, if the room was within the preferred range, then the model deactivated altogether to maintain that ideal status.

Figure 4 shows the results from a sunny day (Fig. 4A) and a cloudy day (Fig. 4B); see movies S3 and S4 for a sped-up video of each of the experiments, respectively. Figure 4 (Ai and Bi) shows the contribution of each term in Eq. 2 to the final output xi (t) as the day passed. When the room was too dark, the output of the hyperbolic tangent function (in the third term) was negative, influencing the model and bringing the final value lower. This can be seen in Fig. 4 (Ai and Bi) at the beginning and the end of the experiment, when the sun was not shining directly into the room, rendering the room too dark. This resulted in lowering the final value, xi (t), enabling full or close to full buckling to allow the maximum amount of light in. Otherwise, when the room was too bright, the third term was positive, adding to the terms (as observed in the region with stacked terms) to flatten the plates and block light. The model, therefore, allowed us to incorporate user preference without affecting the desirable proportional behavior observed from the individualistic approach.

The distributed nature of swarm systems gives them the potential to be resilient to individual failures, common in large-scale systems, provided that the right coordination algorithms are in place. To test whether our system was robust to failures, we introduced deliberate failures in simulation. This was done to ensure that the model could correctly readjust its coefficients and recover in case of failure. The simulations were based on real data collected from the days we ran the SG_od model. Specifically, we tested three scenarios: (i) communication failure, where the robot would only rely on its ambient light sensor (first term); (ii) own sensor failure, where the robot would rely on its neighbors' ambient light sensors (second term) and the room's ambient light sensor (third term); and (iii) room sensor failure, where the robot would rely on its own ambient light sensor (first term) and its neighbors' ambient light sensors (second term).

In simulation, we observed the change of behavior of one of the robots, robot 5, in these three scenarios and compared them with the normal scenario (SG_od model running with no failures) obtained from the real-life experiment. Given that we could not predict how one robot failure would affect the room's ambient light in the second scenario, we assumed it stayed the same, based on real experiment data.

Figure 4 (Aii and Bii) shows the final value, $x_i(t)$, from robot 5 after running the experiment for the three scenarios and against the scenario with no failures. Fig. 4Aii also shows the Pearson correlation coefficient between all of the scenarios for the sunny day (between $r = 0.95$ and $r = 1.00$), and Fig. 4Bii shows the same for the cloudy day (between $r = 0.83$ and $r = 1.00$). The rest of the 3 days (see figs. S3 to S5) showed similar correlations and coefficient distributions, with 2 sunny days and 1 rainy day. The high similarity between all the scenarios, even in rainy and cloudy days, showed that the system did recover from multiple failure scenarios by discarding the failing terms and adjusting the model to adapt successfully [as can be seen in Fig. 4 (Aiii and Biii), which shows the average of the coefficients in each scenario].

Atrium shading in architectural simulation

To demonstrate the capability of the system to scale to large numbers and meet different objectives, we tested a configuration not accessible in our experiments: an atrium with units arranged on a large skylight (see conceptual render in Fig. 5A). In this scenario, we considered tunability in this scaled-up setting, where the objective was to provide selective illuminance: lighting assigned to different sections of a space according to user preference. To investigate this, we conducted a study numerically using Rhino3D/Grasshopper (McNeel) with the plugins Ladybug Tools and Honeybee. With this numerical study, we simulated a south-facing building with dimensions of 20-m depth, 20-m width, and 15-m height and covered the

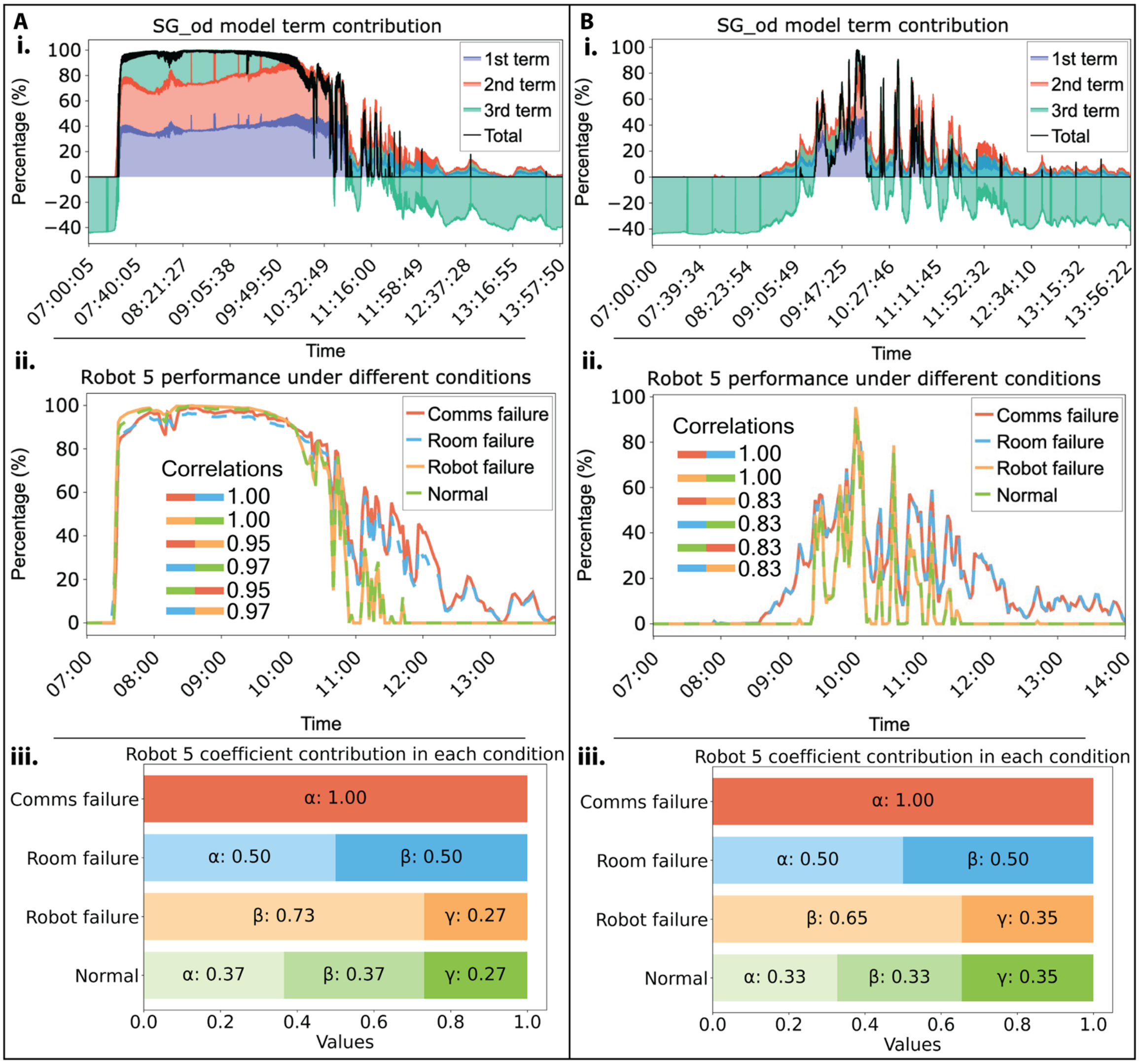


Fig. 4. Adaptive shading experiment results using collective opinion dynamics run from 7:00 to 14:00 in a real office. (**A**) Results from a sunny day. (i) Each term's contribution from the SG_od model (see Eq. 2) represented using a different color, with the final value (total) $x_i(t)$ represented in black. (ii) Final value, $x_i(t)$, when introducing four failure scenarios in simulation to SGbot 5 for the same day: Red is for communication failure, blue is for the room's ambient light sensor failure, orange is for SGbot's ambient light sensor failure, and green is for no failures (normal scenario). The Pearson correlation coefficients between each of the four scenarios are shown on the graph. (iii) Average value of each coefficient contribution (used in Eq. 3) in each failure scenario. (**B**) (i to iii) Results from a cloudy day running the same experiments.

atrium window in a 19-by-19 grid, with each SGbot scaled to ~1 m (see Fig. 5B). The weather data used in simulations were obtained from the Typical Meteorological Year 3 (TMY3) weather file for Trenton Mercer County, New Jersey, USA (WMO 724095), constructed by the National Renewable Energy Laboratory from historical observations for 21 June (*54*). More information on the experiment setup can be found in Supplementary Methods.

In Fig. 5C, we compared the illuminance at 13:00 on 21 June (TMY3) for six shading configurations: open window (no modules), all modules closed, all modules open halfway, all modules maximally open (to the range set in experiments), a horizontal gradient, and a vertical gradient. The results showed that the wide range of continuous deformation of the modules translated to a wide range of illuminance (see illuminance ranges and contrast ratios in Supplementary Methods). As seen by the shifting illuminance gradients in Fig. 5C (v and vi), additional spatial tunability was accessible in a larger system, meaning that the system could accommodate users with different lighting needs in the same space.

In Fig. 5D, we show an example of targeted lighting for different illuminances for different tasks within the same space at 9:00, 13:00, and 17:00 on 21 June (TMY3). Changes in module configuration reflected changes in sun position to ultimately preserve the brighter region centered in the north (lower) portion of the work plane, with gradual dimming elsewhere. The maximum illuminance was kept to ~3000 lux, which was within the typical bounds of the Useful Daylight Index (*55*). The difference in the illuminance plots between Fig. 5D [i (9:00) and ii (13:00)] was 8.5%, and that between Fig. 5D [iii (17:00) and ii (13:00)] was 10.2%. Although module configurations were adjusted manually in this demonstration, as could be done via gestures according to changing preference, algorithmic adjustment

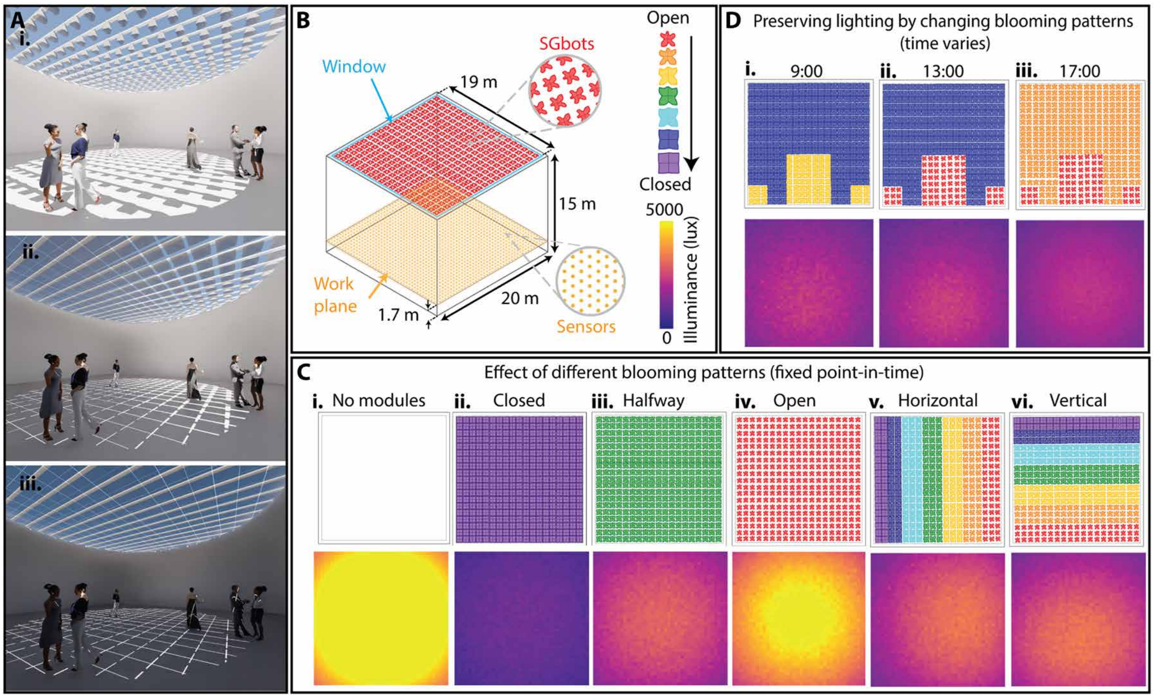


Fig. 5. Simulated shading configurations in an atrium space. (**A**) Conceptual render of modules (created using Blender) as a shading system on an atrium skylight window. Modules open in (i) to allow more light, partially close in (ii), and close entirely for a dim environment in (iii). (**B**) Geometry of the simulated building. Dots on the work plane indicate sensor points. Legends on the right correspond to (C) and (D). (**C**) Skylight module configurations colored by blooming amount as indicated in (B) and resulting illuminance on the work plane colored by illuminance (lux, W/m^2) at 13:00 on 21 June (TMY3) in Mercer County, New Jersey, USA. (**D**) Changing module configurations to preserve similar illuminance conditions throughout the same day, with time stamps indicated above subfigures.

could likely produce more constant illuminance over time. In comparison with traditional shading technologies, from louvered blinds to actuated shading roofs, the Swarm Garden offered independent light targeting in multiple directions with additional degrees of freedom. This multidirectional spatial tunability could be accessed in vertical windows, horizontal atrium ceilings, or even more complex 3D structures such as pavilions (see Fig. 1H).

Case study 2: Swarm robots for creative expression in interior design

The Swarm Garden was designed to be deployed in human spaces, where its effectiveness depended not only on its technical functionality but also on how people perceived and interacted with it to enhance their interior space. To evaluate the user interaction aspect of our system, we needed to test whether the system could demonstrate its ability and durability to function in human environments; withstand the challenges posed by crowds where multiple people interacted with it; engage people positively and effectively, including nonexperts; and allow people to express themselves and shape their interior spaces through the Swarm Garden.

To answer these questions, we hosted a public exhibition showcasing 36 SGbots of the Swarm Garden that was held on 9 April 2024 at Princeton University's Lewis Center for the Arts [see Fig. 6 (A to F)]. The public exhibition was held for 3 hours with mixed media (posters, display cases, and a television with video) displayed throughout the room to provide more background, technical information, motivation, and context for the project. Coauthor A.J. performed a live improvisational dance, equipped with a wearable device (see Materials and Methods) that we designed midway through the exhibition, allowing visitors to observe the emergent behavior of the Swarm Garden. More than 100 attendees visited and interacted with the Swarm Garden. We collected attendee feedback, gauging sentiment from the public about their experience with the Swarm Garden (approved by Princeton University's Institutional Review Board, IRB no. 16722).

We first present the two interaction modes that enabled the crowds to both observe and interact with the swarm, showcasing its self-organizing capabilities and ability to engage with multiple people. We then present the qualitative and quantitative findings from the exhibition, which provided valuable insights for evaluating public sentiments regarding the Swarm Garden. We lastly explore the system's ability to be used as means of expression, by presenting results from an interview conducted with A.J. on her experience dancing with the system using the wearable.

Passive observation of self-organization

In the absence of human interaction, we programmed the Swarm Garden to show patterns of behaviors to create more salient and larger-scale visuals, capturing attendees' attention and highlighting the full range of the system's aesthetic and self-organizing capabilities. Such a dynamic yet passive form of engagement has been shown previously by designers to create beautiful and lively installations that engage crowds (*56*). This mode that we created showed various combinations of ordered and randomized buckling and flattening, as well as light color changes (see Fig. 6C and movie S5). Using the swarm concept of morphogen gradients, the changes appeared to flow and dissipate through the entire swarm from one direction to the other.

Fig. 6. The Swarm Garden public exhibition and audience sentiment results. (**A** and **B**) The exhibition space. (**C**) A snapshot from the passive observation interaction mode. (**D** to **F**) Attendees interacting with the Swarm Garden. (**G**) Word cloud of one-word responses from 57 respondents during the Swarm Garden exhibition. Each participant was able to submit up to three unique words to the word cloud. (**H**) A distribution of words appearing more than once in the responses and a pie chart showing positive/negative word sentiment.

To enable this mode, we developed a localization method (details can be found in Materials and Methods) that allowed SGbots to identify their immediate neighbors and propagate light/blooming accordingly.

Crowd interaction with single SGbots

To directly interact with the swarm and to support multihuman interactions, we developed a mode that allowed users to selectively flatten or buckle individual SGbots. A user could adjust a single SGbot to create a localized shaded area without affecting the entire swarm. Moreover, this mode facilitated multihuman interaction, because several individuals could simultaneously interact with different SGbots without disrupting each other's experiences. This granular control not only enhanced the system's versatility but also promoted collaborative and personalized interactions with the Swarm Garden. This mode was achieved through the SGbot's interaction sensor, which detected hand gestures to trigger flattening or buckling of the plate [see Fig. 6 (D to F) and movie S6]. Details on the implementation of this mode can be found in Supplementary Methods. Other selective modes we developed, including a transient trail of SGbots' LEDs following the user as they passed in front of the Swarm Garden and painting the Swarm Garden by hand-picking different LED lights for individual SGbots, are demonstrated in movies S7 and S8, respectively.

Public exhibition

During the entire 3-hour public exhibition, the Swarm Garden operated smoothly without any issues, demonstrating its durability in handling crowds and switching interaction modes. We ran the passive observation mode for the first 30 min of the exhibition, while attendees were still arriving and familiarizing themselves with the space. The various patterns grabbed attendees' attention, who then were eager to start interacting more closely with the swarm. Therefore, we enabled crowd interaction, allowing attendees to manipulate the plate displacement of the SGbots, offering a hands-on understanding of the system's adaptability and responsiveness. This allowed many users to interact with the swarm at once. Midway through the exhibition, A.J. performed with the swarm. After her performance, we reenabled crowd interaction so the attendees could continue engaging with the swarm. We then surveyed the attendees by requesting that they optionally fill out a form asking "Describe your experience with Swarm Garden in one word." They were also prompted to provide any other feedback on the exhibition in an open-ended text format.

Fifty-seven unique respondents submitted a word or multiple words (up to three) to the word cloud, and 21 respondents left additional comments in a general feedback and reflections form. All responses can be found in data files S1 (word cloud) and S2 (feedback). The word cloud, shown in Fig. 6G, immediately showed a general positive sentiment across the largest words, with the most popular words being "cool" (frequency = 9) and "interactive" (frequency = 8), as shown in the distribution in Fig. 6H. To more formally and objectively define the overall audience sentiment, Python Natural Language Toolkit's VADER (Valence Aware Dictionary for Sentiment Reasoning) sentiment analysis tools were used to extract sentiment scores on the basis of the words submitted to the word cloud. By manually assigning negative scores to words such as "manmade," "crowded," and "dim" that were otherwise interpreted as neutral by the model, the sentiments could be categorized more accurately. The audience responded with overwhelmingly positive sentiments (95.8% positive sentiments and 4.2% negative sentiments, shown in Fig. 6H). We supported this finding by the strong positive sentiments expressed by most of the open-ended form responses: 19 of 21 were positive, 1 was a neutral question, and 1 was a constructive criticism (see Table 1 for examples).

The Swarm Garden's "floral," "colorful," and "beautiful" appearance left the attendees generally with an "inspiring" feeling that was triggered with their "interactive" experience while "engaging" with the swarm. The Swarm Garden seemed to have succeeded at capturing the attendees' attention, with words such as "captivating" and "mesmerizing" frequently appearing, and leaving them with a "calming" and "fresh" feeling. The highly positive reception and enthusiasm suggested that dynamic and responsive architectural swarm interiors have the potential to contribute to a sense of joy and well-being.

Creative expression through dance

Single interactions allowed individuals direct control over the SGbots in the Swarm Garden. A more holistic interaction, where users influence the swarm's self-organization, introduced a balance between predictability driven by the user control and randomness driven by the swarm's emergent behavior. This dynamic control could start a two-way conversation between user and swarm, creating a unique experience each time, encouraging improvisation, exploration, and creative expression.

To further investigate the Swarm Garden's performative potential, we collaborated with coauthor A.J., a professional dancer with 19 years of experience across various styles, including social dance, ballet, contemporary dance, and jazz funk. Equipped with the wearable, A.J. engaged with the Swarm Garden as a dynamic dance partner, allowing it to complement and interact with her movements throughout the performance. A.J. engaged with the swarm in improvisational dance twice privately with the rest of the Swarm Garden team (see movie S9 for a performance) and once in front of a public audience at the public exhibition we hosted with the Swarm Garden. We then interviewed A.J. on her experience improvising with the Swarm Garden, which allowed us to study and analyze how the interaction influenced her movements, perception of dance partnership, and artistic expression.

We designed a lightweight wrist wearable (see Fig. 7A), motivated by the idea that a dancer could use natural arm movements in the choreography to guide and shape the response of the swarm. The wearable mapped arm movements to different LED color responses, creating a dialogue between dancer and swarm through body movement and light. The direction of arm movement in all three axes was detected through an accelerometer on the Arduino Nicla Vision in the wearable device, and depending on the direction, the LEDs of the SGbots responded differently (see movie S10 for the responses). The y-axis movement was consistent every time, allowing the user to either turn all LEDs to green (negative y axis) or turn off all LEDs (positive y axis). A movement in the positive x axis generated a random number between 0 and 35 to pick a random SGbot to propagate the color fuchsia from those SGbots to the whole swarm. A movement in the z axis picked a random SGbot to propagate the color blue only to the SGbots to the left of the chosen SGbot (negative z axis) or the color pink only to the SGbots to the right of the chosen SGbot (positive z axis). In this way, the arm movements corresponded to both predictable and emergent responses from the swarm, resulting in a different performance effect even if the choreography remained the same. We next discuss results from the interview on how this interaction mode influenced the dancer in an improvisational setting [see Fig. 7 (B to F) for snapshots of the dances], where the dancer could modify the choreography in real time in response to observations of the swarm.

Embodied interaction. When reflecting on her experience improvising with the Swarm Garden, A.J. described their relationship as a "partnership defined by negotiation." Because of the swarm's inherent unpredictability, the roles of a dance leader and follower became ambiguous. Instead, they were both partners influencing one another; instead of exerting direct control, she engaged in a dynamic "push and pull" interaction, adjusting her movements in response to the swarm's reactions and creating movements that would elicit different responses from the swarm. Given that sometimes the cues she gave the swarm through her dance movements resulted in an unpredictable behavior, it felt to her as if the swarm was "alive."

Table 1. Example quotes from the feedback form available to attendees at the Swarm Garden public exhibition.

Response type	Quotes
Positive	"Such a beautiful and vibrant experience!"
	"Such a unique display of robotics! The dance interaction is amazing!"
	"This is sooo cool, it was so amazing to watch and the technology is even crazier!"
	"I loved how interactive the project is! This is frankly amazing!"
	"Lovely visuals and great interactive experience"
Neutral	"Can they be programmed to create certain swarm patterns?"
Critiques	"Increase the harmony of the swarm. Make it move more quickly."

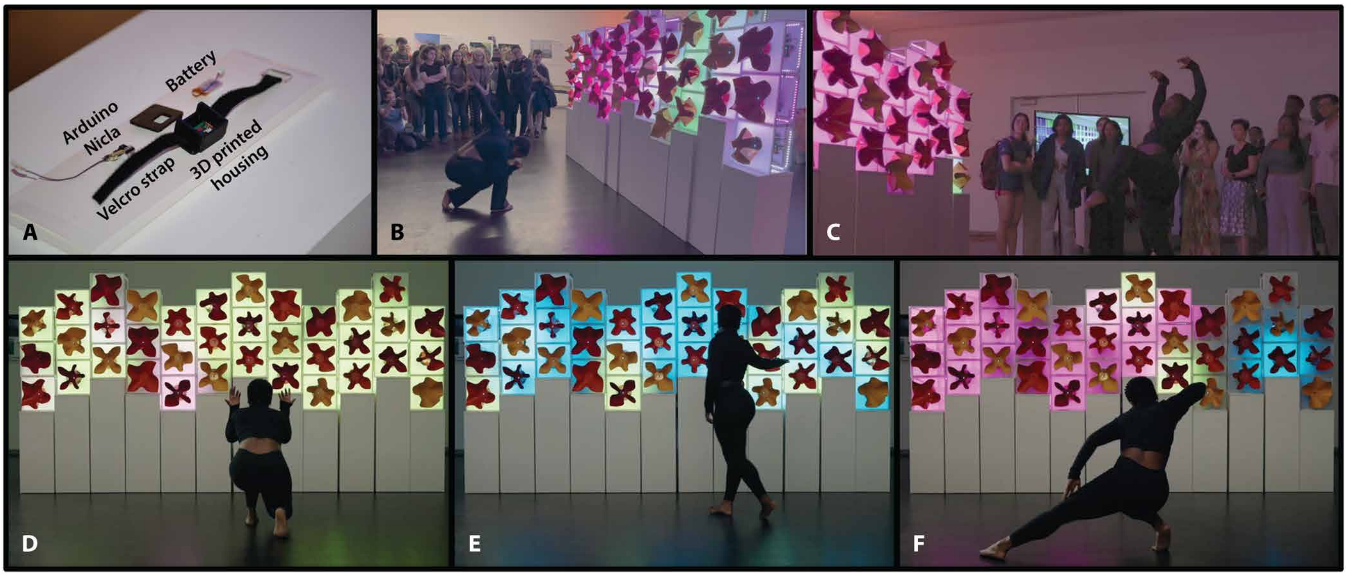


Fig. 7. Improvisational dance performance with the wearable device. (**A**) Wearable device components. (**B** and **C**) Snapshots from the public exhibition improvisational dance performance. (**D** to **F**) Different movements causing different responses from the Swarm Garden.

Physical aspects. Although the wearable itself was comfortable and did not restrict movement, A.J. noted that dancing with the swarm heightened her awareness of her own body. In particular, it brought attention to her arm movements—a part she had often perceived as "passive" in her dancing—which took on a more active role in shaping her dialogue with the swarm. However, physical constraints emerged because of the limitations of the technology. A.J. had to remain within specific spatial boundaries to maintain communication between the wearable and the swarm, subtly influencing the way she moved and engaged with the system.

Audience interaction. A.J. explained that, during her live performance, although there were moments when she simply went with the flow without focusing on the Swarm Garden's actions, she was also conscious of fully showcasing the system's capabilities, particularly through her arm movements. This awareness inspired her to "search her mind" for movements that could elicit different responses from the swarm. In this way, she not only influenced the swarm's behavior but was also influenced by it, prompting her to explore ways of expressing herself through dance. Through this exploration, A.J. developed what she described as a "secret language" with the swarm. Unlike the audience, who remained unaware of which movements triggered specific responses from the Swarm Garden, she understood these subtle cues, deepening her connection to the swarm. This sense of synchronization made her feel "locked in the zone" and as though she and the swarm were "seeing eye to eye." This partnership between dancer and swarm captivated the audience, who later approached A.J. with questions, intrigued by the nature of this partnership.

Artistic expression. A.J. described the experience as one that "opened up for me the limits of what expression and interaction can be within dance." She explained that the Swarm Garden expanded her understanding of how dance could exist beyond the traditional stage, allowing technology to foster new forms of partnership and creativity, essentially transforming it into a new kind of "proscenium." Reflecting further, A.J. saw the Swarm Garden as an exciting form of performative art, an interactive exhibition that, like an installation in a museum that could be activated by passersby, could also be activated through the medium of dance.

DISCUSSION

Architectural swarms have the potential to create adaptive, responsive environments that shape indoor spaces and react to outdoor conditions to meet occupants' needs. The Swarm Garden is a proof of concept that leverages swarm robotics and swarm intelligence algorithms to create an architectural façade that is capable of complex self-organized responses to environment and people. The Swarm Garden is envisioned to be deployed in different configurations and diverse spaces, such as vertically on large windows, horizontally in atrium spaces, or in theaters to act as an extra expressive dimension for performative arts.

The Swarm Garden functions as an adaptive shading mechanism, responding proportionally to daylight. The SG_od model enabled self-organization and handled multiple failure modes, such as communication losses and sensor malfunctions. User preference was incorporated by factoring preferred room ambient light into the model. Results showed high correlation between communication loss and room sensor failure scenarios and less to the normal scenarios, due to the removal of the third term in the model in both scenarios (reflecting removal of user preference). This shows the substantial effect that the user preference can have on the model. Adjusting the coefficient of the third term higher or lower could allow users to add more or less control on lighting preference in the future. Other factors, such as time of day or temperature, can be added or swapped in the model with adjustable coefficients as well. Another high correlation was between the normal scenario and the robot sensor failure scenario because robots and their neighbors shared similar opinions in such a small window. As the swarm expands to hundreds or thousands of robots and is deployed across bigger windows where sunlight intensity varies, the SG_od model will operate on the basis of the immediate neighborhood of each robot rather than aggregating input from the entire swarm. This localized approach ensures that robots respond to their specific lighting conditions while being robust to failure, given that distant neighbors may experience different sunlight intensities because of the sun's movement. However, far neighbors could still play a role in predicting the sun's trajectory, enabling adaptive responses across the entire system.

Crowd interaction with the Swarm Garden provided valuable feedback for refining its design. Attendees particularly appreciated the system's aesthetics and nature-inspired look. Our work spans a spectrum of interaction modalities with varying levels of user agency—passive observation, crowd interaction, and creative expression, with user agency increasing from less to more, respectively. In the future, we aim to enhance user agency through speech- and tablet-based interfaces for greater accessibility and inclusivity (see Supplementary Methods). Learning-based methods may further increase user agency over time. Some feedback from attendees suggested introducing tunable parameters, such as the speed of blooming. Other designs exploring alternative blooming mechanisms could provide enhanced speed and capabilities (see Supplementary Methods). We used LED responses with a fast-paced creative application like dance for its quicker feedback over blooming. However, the contrast between fast-reacting lights and slower blooming could offer another expressive layer worth exploring, such as correlating blooming to the music. Another promising direction is collaborating with choreographers to explore sensor placement on different body parts. As the dancer noted, the wrist was comfortable and expressive for her, but future iterations could explore alternatives, such as belts or anklets, that may be better suited to dance forms that involve different body movements. The successful transformation of the Swarm Garden into a creative partner in dance demonstrates the potential for the system to inspire different forms of creative expression. Results from the interview with the dancer reveal how artists can form a "partnership defined by negotiation" with the swarm. This partnership moves beyond simple control to create interactions that are personally meaningful to the artist and captivating to the audience. By reflecting on both audience-robot (through the survey) and artist-robot (through the interview) interactions, our work contributes to, and deepens our understanding of, human-swarm interaction in performative contexts.

As a step toward integrating the Swarm Garden into human spaces, we plan to collaborate with architects to evaluate the feasibility of long-term deployments in various configurations and places. Although plastic deformation resulting from stress focusing (*57*) is essential to the blooming-via-buckling process, future work could explore the use of more sustainable and more resilient materials than those used in our demonstrations. A promising future direction is to modify the sheet's structure using kirigami-inspired cuts (*58*) to lower actuation power. Long-term user studies will also be conducted to assess user adoption over time and identify opportunities to further customize the system to meet user needs and preferences.

We envision a future where the built environment is increasingly inspired by living architectures, creating façades that constantly adapt to their surroundings and occupants. The Swarm Garden offers a glimpse into that future: an architectural swarm that collectively responds to sunlight and human interaction. It further shapes occupants' spaces by being animated with movement, vibrant with colors, and beautiful in appearance, inspiring creativity and expression.

MATERIALS AND METHODS

The SGbot design

Each SGbot's dimensions are 32.5 cm by 32.5 cm by 18.1 cm. The SGbot's plate is made of a 0.127-mm-thick plastic shimstock sheet and is secured with a top and bottom clamp. A base printed circuit board (PCB) on the back distributes power and connects the sensors, LED strip, and motor controller to an adaptor PCB that houses the Nicla. Further assembly and electronics details can be found in Supplementary Methods.

The wearable device design

The wearable device, shown in Fig. 7A, was designed to act as a bracelet to be worn around the wrist. It could be fastened with a Velcro strap that could be adjusted depending on different wrist sizes to accommodate diverse users. The wearable consisted of a switch to easily turn it on and off, a 3.3-V battery, and an Arduino Nicla, all connected through a stripboard. The components were all neatly hosted in a 3D-printed case that the Velcro ran through. The Nicla had an inertial measurement unit on board, which was used to detect the direction of wrist movement.

Localization and neighbor identification

For passive observation and wearable interactions, SGbots' immediate neighbors were tracked using a localization algorithm. Each SGbot had a unique AprilTag on its back, and a wide-angle camera recorded the 2D positions of all tags. The six nearest neighbors of each SGbot were identified and assigned fixed relative positions for direction-specific messaging. The camera continuously updated each SGbot's neighbor list to reflect changes in swarm configuration or maintain connectivity even if individual SGbots failed. Additional details on the localization process are provided in Supplementary Methods.

Statistical analysis

We used the Pearson correlation coefficient to compare the ambient-light and encoding sensor timeseries data for both the individualistic and collective adaptive shading experiments, as well as to assess similarity under different failure modes. For all experiments, we report the P values, means, and SDs across n trials.

Supplementary Materials

The PDF file includes:
Methods
Figs. S1 to S11
Tables S1 to S6
Legends for movies S1 to S10
Legends for data files S1 and S2
References (*60*, *61*)

Other Supplementary Material for this manuscript includes the following:
Movies S1 to S10
Data files S1 and S2
MDAR Reproducibility Checklist

REFERENCES AND NOTES

1. S. Camazine, J.-L. Deneubourg, N. R. Franks, J. Sneyd, G. Theraulaz, E. Bonabeau, *Self-Organization in Biological Systems* (Princeton Univ. Press, 2003).
2. V. Charpentier, P. Hannequart, S. Adriaenssens, O. Baverel, E. Viglino, S. Eisenman, Kinematic amplification strategies in plants and engineering. *Smart Mater. Struct.* **26**, 063002 (2017).
3. H. F. McCreery, Z. A. Dix, M. D. Breed, R. Nagpal, Collective strategy for obstacle navigation during cooperative transport by ants. *J. Exp. Biol.* **219**, 3366–3375 (2016).

4. M. Brambilla, E. Ferrante, M. Birattari, M. Dorigo, Swarm robotics: A review from the swarm engineering perspective. *Swarm Intell.* **7**, 1–41 (2013).
5. S. Adriaenssens, L. Rhode-Barbarigos, A. Kilian, O. Baverel, V. Charpentier, M. Horner, D. Buzatu, Dialectic form finding of passive and adaptive shading enclosures. *Energies* **7**, 5201–5220 (2014).
6. M. Hemberg, U.-M. O'Reilly, A. Menges, K. Jonas, M. da Costa Gonçalves, S. R. Fuchs, in *Genr8: Architects' Experience with an Emergent Design Tool* (Springer, 2008), pp. 167–188.
7. U.-M. O'Reilly, M. Hemberg, Integrating generative growth and evolutionary computation for form exploration. *Genet. Program. Evolvable Mach.* **8**, 163–186 (2007).
8. T. Hai, A. S. El-Shafay, A. Alizadeh, K. Kulshreshtha, S. F. Almojil, A. I. Almohana, A. Alali, Improved locust swarm optimization algorithm applied for building retrofitting based on the green policy of buildings. *J. Build. Eng.* **70**, 106274 (2023).
9. N. Delgarm, B. Sajadi, F. Kowsary, S. Delgarm, Multi-objective optimization of the building energy performance: A simulation-based approach by means of particle swarm optimization (PSO). *Appl. Energy* **170**, 293–303 (2016).
10. M. K. Heinrich, S. Von Mammen, D. N. Hofstadler, M. Wahby, P. Zahadat, T. Skrzypczak, M. D. Soorati, R. Krela, W. Kwiatkowski, T. Schmickl, P. Ayres, K. Stoy, H. Hamann, Constructing living buildings: A review of relevant technologies for a novel application of biohybrid robotics. *J. R. Soc. Interface* **16**, 20190238 (2019).
11. A. Çelekli, İ. Yeşildağ, Ö. E. Zariç, Green building future: Algal application technology. *J. Sustain. Constr. Mater. Technol.* **9**, 199–210 (2024).
12. M. Wahby, M. K. Heinrich, D. N. Hofstadler, E. Neufeld, I. Kuksin, P. Zahadat, T. Schmickl, P. Ayres, H. Hamann, Autonomously shaping natural climbing plants: A bio-hybrid approach. *R. Soc. Open Sci.* **5**, 180296 (2018).
13. M. Brzezicki, A systematic review of the most recent concepts in kinetic shading systems with a focus on biomimetics: A motion/deformation analysis. *Sustainability* **16**, 5697 (2024).
14. N. Heidari Matin, A. Eydgahi, Technologies used in responsive facade systems: A comparative study. *Intell. Build. Int.* **14**, 54–73 (2022).
15. F. Sommese, L. Badarnah, G. Ausiello, A critical review of biomimetic building envelopes: Towards a bio-adaptive model from nature to architecture. *Renew. Sustain. Energy Rev.* **169**, 112850 (2022).
16. A. M. A. Faragalla, S. Asadi, Biomimetic design for adaptive building façades: A paradigm shift towards environmentally conscious architecture. *Energies* **15**, 5390 (2022).
17. E. Vazquez, D. Correa, S. Poppinga, A review of and taxonomy for elastic kinetic building envelopes. *J. Build. Eng.* **82**, 108227 (2024).
18. M. Gonçalves, A. Figueiredo, R. M. S. F. Almeida, R. Vicente, Dynamic façades in buildings: A systematic review across thermal comfort, energy efficiency and daylight performance. *Renew. Sustain. Energy Rev.* **199**, 114474 (2024).
19. M. Pesenti, G. Masera, F. Fiorito, Exploration of adaptive origami shading concepts through integrated dynamic simulations. *J. Archit. Eng.* **24**, 04018022-1 (2018).
20. L. Le-Thanh, T. Le-Duc, H. Ngo-Minh, Q.-H. Nguyen, H. Nguyen-Xuan, Optimal design of an Origami-inspired kinetic façade by balancing composite motion optimization for improving daylight performance and energy efficiency. *Energy* **219**, 119557 (2021).
21. M. Meloni, J. Cai, Q. Zhang, D. Sang-Hoon Lee, M. Li, R. Ma, T. E. Parashkevov, J. Feng, Engineering origami: A comprehensive review of recent applications, design methods, and tools. *Adv. Sci.* **8**, 2000636 (2021).
22. D. Misseroni, P. P. Pratapa, K. Liu, B. Kresling, Y. Chen, C. Daraio, G. H. Paulino, Origami engineering. *Nat. Rev. Methods Primers* **4**, 40 (2024).
23. Y. Li, Y. Zhao, Y. Chi, Y. Hong, J. Yin, Shape-morphing materials and structures for energy-efficient building envelopes. *Mater. Today Energy* **22**, 100874 (2021).
24. T. Cheng, Y. Tahouni, E. S. Sahin, K. Ulrich, S. Lajewski, C. Bonten, D. Wood, J. Rühe, T. Speck, A. Menges, Weather-responsive adaptive shading through biobased and bioinspired hygromorphic 4D-printing. *Nat. Commun.* **15**, 10366 (2024).
25. D. Sung, Smart geometries for smart materials: Taming thermobimetals to behave. *J. Archit. Educ.* **70**, 96–106 (2016).
26. M. Dorigo, G. Theraulaz, V. Trianni, Swarm robotics: Past, present, and future [point of view]. *Proc. IEEE* **109**, 1152–1165 (2021).
27. K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, M. Kovac, A review of collective robotic construction. *Sci. Robot.* **4**, eaau8479 (2019).
28. F. Augugliaro, S. Lupashin, M. Hamer, C. Male, M. Hehn, M. W. Mueller, J. S. Willmann, F. Gramazio, M. Kohler, R. D'Andrea, The Flight Assembled Architecture installation: Cooperative construction with flying machines. *IEEE Control Syst. Mag.* **34**, 46–64 (2014).
29. S. Parascho, I. X. Han, S. Walker, A. Beghini, E. P. G. Bruun, S. Adriaenssens, Robotic vault: A cooperative robotic assembly method for brick vault construction. *Constr. Robot.* **4**, 117–126 (2020).
30. J. Werfel, K. Petersen, R. Nagpal, Designing collective behavior in a termite-inspired robot construction team. *Science* **343**, 754–758 (2014).
31. S. Hauser, M. Mutlu, P.-A. Léziart, H. Khodr, A. Bernardino, A. J. Ijspeert, Roombots extended: Challenges in the next generation of self-reconfigurable modular robots and their application in adaptive and assistive furniture. *Robot. Auton. Syst.* **127**, 103467 (2020).
32. L. Tang, D. Rüegg, R. Zhang, A. Bolotnikova, J. Rabaey, A. Ijspeert, Velocity potential field modulation for dense coordination of polytopic swarms and its application to assistive robotic furniture. *IEEE Robot. Autom. Lett.* **10**, 7452–7459 (2025).
33. F. Mondada, M. Bonani, F. Riedo, M. Briod, L. Pereyre, P. Retornaz, S. Magnenat, Bringing robotics to formal education: The Thymio open-source hardware robot. *IEEE Robot. Autom. Mag.* **24**, 77–85 (2017).
34. A. Ozgur, S. Lemaignan, W. Johal, M. Beltran, M. Briod, L. Pereyre, F. Mondada, P. Dillenbourg, "Cellulo: Versatile handheld robots for education," in *Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, HRI '17 (Association for Computing Machinery, 2017), pp. 119–127.
35. M. Alhafnawi, S. Hauert, P. O'Dowd, "Robotic canvas: Interactive painting onto robot swarms," in *Proceedings of the ALIFE 2020: The 2020 Conference on Artificial Life* (MIT Press, 2020), pp. 163–170.
36. M. Santos, G. Notomista, S. Mayya, M. Egerstedt, Interactive multi-robot painting through colored motion trails. *Front. Robot. AI* **7**, 580415 (2020).
37. N. Correll, N. Farrow, S. Ma, "HoneyComb: A platform for computational robotic materials," in *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*, TEI '13 (Association for Computing Machinery, 2013), pp. 419–422.
38. M. Alhafnawi, E. R. Hunt, S. Lemaignan, P. O'Dowd, S. Hauert, "MOSAIX: A swarm of robot tiles for social human-swarm interaction," in *2022 International Conference on Robotics and Automation (ICRA)* (IEEE, 2022), pp. 6882–6888.
39. M. Le Goc, L. H. Kim, A. Parsaei, J.-D. Fekete, P. Dragicevic, S. Follmer, "Zooids: Building blocks for swarm user interfaces," in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, UIST '16 (Association for Computing Machinery, 2016), pp. 97–109.
40. F. Meggers, D. Aviv, V. Charpentier, E. Teitelbaum, A. Ainslie, S. Adriaenssens, "Co-optimization of solar tracking for shading and photovoltaic energy conversion," in *Proceedings of Building Simulation 2017: 15th Conference of IBPSA*, vol. 15 of *Building Simulation*, C. S. Barnaby, M. Wetter, Eds. [IBPSA (International Building Performance Simulation Association), 2017)], pp. 2224–2231.
41. V. Charpentier, F. Meggers, S. Adriaenssens, O. Baverel, Occupant-centered optimization framework to evaluate and design new dynamic shading typologies. *PLOS ONE* **15**, e0231554 (2020).
42. T. Solano, A. Bernal, D. Mora, M. Chen Austin, How bio-inspired solutions have influenced the built environment design in hot and humid climates. *Front. Built Environ.* **9**, 10.3389/fbuil.2023.1267757 (2023).
43. Y. Zeng, H. Sun, B. Lin, Q. Zhang, Non-visual effects of office light environment: Field evaluation, model comparison, and spectral analysis. *Build. Environ.* **197**, 107859 (2021).
44. P. Zumthor, "Atmospheres: Architectural environments. surrounding objects," in *Atmospheres* (Birkhäuser, 2006).
45. R. Scruton, *The Aesthetics of Architecture* (Princeton Univ. Press, 2021).
46. A. LaViers, Robots and dance: A promising young alchemy. *Annu. Rev. Control Robot. Auton. Syst.* **8**, 323–350 (2025).
47. L. B. Rosselló, M. Alkilabi, E. Tuci, H. Bersini, A. Reina, "Emergent orchestras: A modular framework for musical robot swarms," in *Proceedings of the ALIFE 2020: The 2020 Conference on Artificial Life* (MIT Press, 2024), pp. 29–37.
48. D. St-Onge, U. Côté-Allard, K. Glette, B. Gosselin, G. Beltrame, Engaging with robotic swarms: Commands from expressive motion. *ACM Trans. Hum. Robot. Interact.* **8**, 1–26 (2019).
49. L. Stein-Montalvo, A. Guerra, K. Almeida, O. Kodio, D. P. Holmes, Wrinkling and developable cones in centrally confined sheets. *Phys. Rev. E* **108**, 035002 (2023).
50. K. A. Seffen, Truncated cones from indenting a clamped disk. *Phys. Rev. E* **110**, 035002 (2024).
51. N. Leonard, A. Bizyaeva, A. Franci, Fast and flexible multiagent decision-making. *Annu. Rev. Control Robot. Auton. Syst.* **7**, 19–45 (2024).
52. R. Gray, A. Franci, V. Srivastava, N. E. Leonard, Multiagent decision-making dynamics inspired by honeybees. *IEEE Trans Control Netw Syst* **5**, 793–806 (2018).
53. A. Bizyaeva, A. Franci, N. E. Leonard, "Sustained oscillations in multi-topic belief dynamics over signed networks," in *2023 American Control Conference (ACC)* (IEEE, 2023), pp. 4296–4301.
54. S. Wilcox, W. Marion, Users manual for TMY3 data sets (revised) (No. NREL/TP-581-43156, National Renewable Energy Lab, 2008).
55. J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, "Daylighting metrics: Is there a relation between useful daylight illuminance and daylight glare probability?" in *Proceedings of the Building Simulation and Optimization Conference BSO12* (IBPSA, 2012), pp. 189–196.
56. M. Salimi, *Swarm Systems in Art and Architecture: State of the Art* (Springer Nature, 2021).
57. T. A. Witten, Stress focusing in elastic sheets. *Rev. Mod. Phys.* **79**, 643–675 (2007).
58. L. Stein-Montalvo, L. Ding, M. Hultmark, S. Adriaenssens, E. Bou-Zeid, Kirigami-inspired wind steering for natural ventilation. *J. Wind Eng. Ind. Aerodyn.* **246**, 105667 (2024).
59. P. Zurn, D. S. Bassett, N. C. Rust, The Citation Diversity Statement: A practice of transparency, a way of life. *Trends Cogn. Sci.* **24**, 669–672 (2020).

60. C. Hutto, E. Gilbert, VADER: A parsimonious rule-based model for sentiment analysis of social media text. *Proc. Int. AAAI Conf. Web Social Media* **8**, 216–225 (2014).
61. J. Devlin, M.-W. Chang, K. Lee, K. Toutanova, "BERT: Pre-training of deep bidirectional transformers for language understanding," in *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, J. Burstein, C. Doran, T. Solorio, Eds. (Association for Computational Linguistics, 2019), pp. 4171–4186.

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