Formica Forma

Explorations in Insect-Robot Collaboration for Emergent Design and Manufacturing

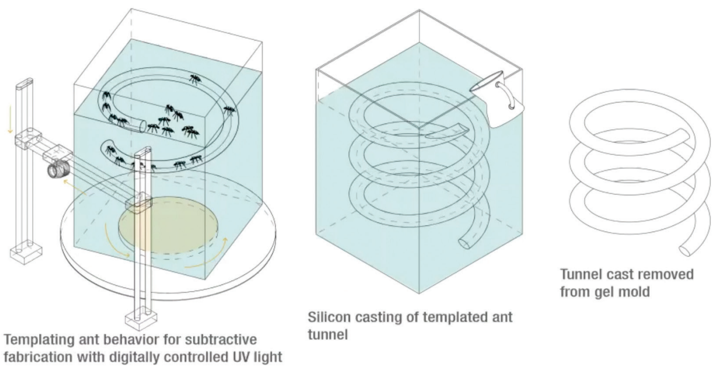
Andrea Ling
ETH Zurich

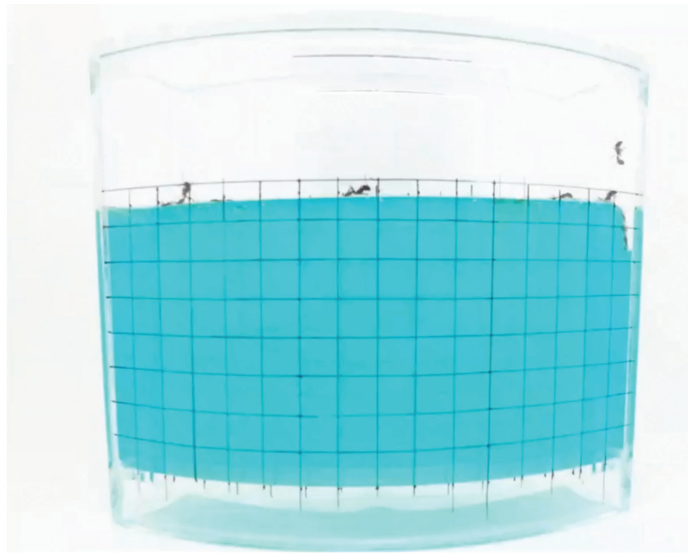
Mahshid Moghadasi
Cornell University

Kowin Shi
Cornell University

Junghsien Wei
Cornell University

Dr. Kirstin Peterson
Cornell University





1, 2

1 Possible experimental structure where ants can dig out tunnels in nutrient ant gel with appropriate UV stimulus. Tunnel in gel can then be cast.

2 Control arena (16 × 14 × 3 cm), marked with 1 × 1 cm grid, with no UV light stimulus, 10 ants digging over 7 days.

ABSTRACT

Hybrid robot systems that cooperate with live organisms is an active area of research, in part to leverage biological advantages such as adaptivity, resilience, and sustainability. *Formica Forma* explores new possibilities of codesigning and cofabricating in partnership with Western Harvester ants to build forms that would be challenging with industrial techniques.

Using a robotically controlled UV light (350–405 nm) as an environmental stimulus to bias digging behavior, we guide 600 ants to dig ~141 cm of tunnels in transparent ant gel over 646 hours. Predictability, fidelity to the UV source, repeatability, dig efficiency, amount of ant activity, and tunnel preference were studied. The resulting branching tunnels were cast in silicone to demonstrate the ability to harness this in subtractive fabrication with inexpensive, self-maintaining biological fabricators.

Results showed that ants can follow the UV light as a path guide (when the light is moving) or target it as a goal (when the light is both moving and static), with longer digging effect from the moving UV stimulus. Ants showed high fidelity to the light path, aligning their tunnel direction exactly with changes in the UV position, tuning the fabrication in real-time with environmental alterations. Population size did not seem to affect digging speed or efficiency, and the ants' preexisting preferences factored into which tunnels were dug out.

The research develops a hybrid biodigital way of working with biological swarms where the individual agency and the intrinsic stochasticity of the system offer possibilities in real-time adaptability and programmability through environmental templating.

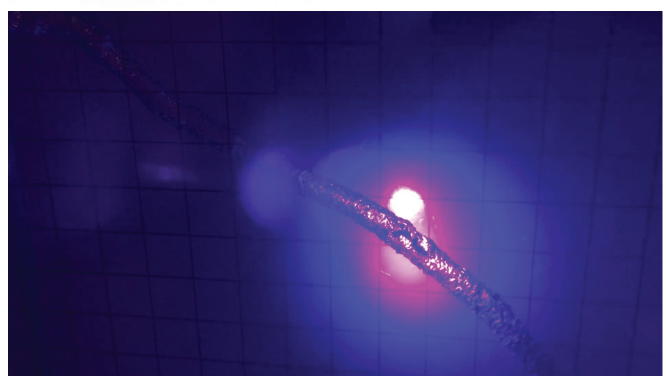
INTRODUCTION: INSECT AS PARTNER

In this paper, we focus on merging digital and biological fabrication to leverage biological advantages, particularly those associated with swarm systems, such as adaptability, sustainability, and robustness, with the design intentionality afforded by digital technologies. Projects such as Ren Ri's *Yuansu* beehive sculptures (Cascone 2014), Mediated Matter's *Silk Pavilion* (Oxman et al. 2014), and Agnieszka Kurant's *AAI* termite mounds (Walsh 2015) show cultural and engineering potential when human intent partners with biological agency, where design effort is placed not on developing artifact form but, rather, templating environmental conditions and designing processes for novel fabrication technologies.

Designing with biological systems, however, often means one is incorporating a degree of inherent agency and loss of control into the system, and requires an adjustment in design thinking for successful collaboration. We use Western harvester ants (*Pogonomyrmex occidentalis*), which are attracted to close-range UV light (Kayser 2018), and a robot-actuated UV light source to modify ant behavior as they construct tunnels in transparent nutrient gel. Six hundred ants were monitored over a period of 646 hours, digging ~141 cm of UV-templated tunnels, using the light as both a guide and target. The hypothesis was that the ant response is significant and accurate enough to direct the overall structural direction, despite individual level variance in tunnel direction. We were able to show preliminary success based on this idea with data collected from eight different experiments. More importantly, this project proves the feasibility of design with hybrid authorship instead of a strictly deterministic and human-generated model, a unique feature offered by this biodigital cooperative system.

The work develops methodologies towards adaptable sustainable fabrication through interaction with a swarm of ants and shows that their constructed tunnels are consistently biased by the presence of UV light but are also dependent on low-level stochastic interactions. We found that the ant-robot collaboration could form features that would be difficult with digital manufacturing and that the system was adaptable and robust in response to variability among individuals. The bio-hybrid approach, however, requires a shift in expectations due to the inherent agency and stochasticity of the system. The work offers insight on how to adjust design protocols in response to an inherently noisy aggregate system, with potential application to other hybrid biological-digital systems as well as in robotic swarm systems where individual agents have a high degree of autonomy and stochastic behavior.

3



4, 5

3 *Silk Pavilion II*, 2020, The Museum of Modern Art, Neri Oxman & the Mediated Matter Group. This second iteration of the pavilion employed 17,532 silk worms on a robotically controlled scaffold to spin the silk skin of the structure.

4 *Pogonomyrmex occidentalis*, 600 specimens ordered from commercial supplier.

5 *Pogonomyrmex occidentalis* is attracted to close-range UV light ~ 350–405 nm wavelength.

BACKGROUND

Employing biological organisms as viable manufacturing platforms has gained traction in the field of synthetic biology and living material synthesis, where microbial organisms are used for their ability to procreate, synthesize new material, sense environmental conditions, and respond to disturbances in such conditions (Gilbert, Tang et al. 2019; Nguyen et al. 2018). Parallel efforts have only just begun in partnering biological organisms with robotic systems and larger-scale fabrication platforms. The term "partner" is used specifically, as one of the long-term goals is to develop bio-hybrid systems that favor mutualism between organism and machine over exploitation. The logic is that a symbiotic system, beneficial to both parties, can be ethical and will persist far longer than a system that exploits or kills the biological partner. The challenge, then, is to learn about the behavior of these autonomous partners such that the designed system can indeed be beneficial and will have a reliable degree of predictability.

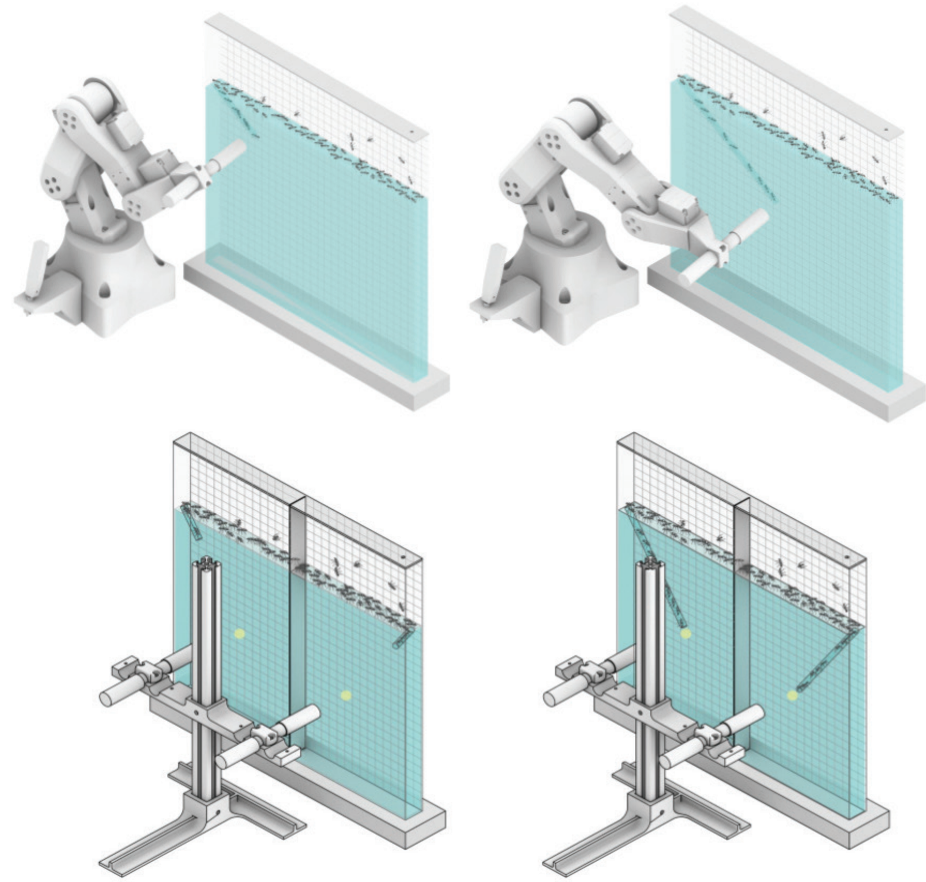
In the *Silk Pavilion I,* the Mediated Matter group worked with 6,500 live silkworms to construct an architectural-scale pavilion. The group harnessed the silkworms' ability to adapt to different scaffold conditions, including variations in local temperature, aperture size, and z-height, to create a variable-density cladding on top of a parametrically designed and robotically fabricated scaffold that is configured by humans into a geodesic dome. Rather than boiling silk cocoons (thus sacrificing the silkworms) in order to harvest silk—as is done industrially—the silk remains on the pavilion and the worms are free to pupate and turn into moths. With his *Yuansu* series of honeycomb sculptures, the artist Ren Ri influences how the bees construct their hives by manually changing the orientation of their enclosure every seven days; the human artist dictates overall directionality in the shape of the hive but relinquishes fine-scale geometric authorship to the bees. In *Project coelicolor,* designer Natsai Audrey-Chiesza employs *Streptomyces coelicolor,* a common soil bacteria that produces vibrant magenta to indigo pigments, as painters of patterns on silk, setting color by precisely controlling nutrient type, level, pH, and temperature, as well as fixing shape by creating jigs within which the bacteria can work.

In all these projects, programmability and predictability of the outcome depend on setting the appropriate environmental conditions and stimuli to induce corresponding bottom-up behavior from the organisms to meet top-down expectations. We use similar stigmergic principles of coordination to guide our proposed collaboration with *Pogonomyrmex occidentalis*. Harvester ants demonstrate complex behaviors such as construction and foraging, which are the result of interactions that arise from individual stochastic occurrences (Gordon 2002). Coherent collective behavior emerges as the sum of these simple, distinct response-stimuli occurrences. Stimuli can be a variety of environmental cues; for instance, many species of ants use the angle of light polarization in the UV spectrum to navigate between foraging sites and their nests (Freas and Schultheiss 2018), while others use changes in relative humidity as a trigger to change the layout of their nest. Significantly for this work, *P. occidentalis* are highly influenced by ultraviolet light (350–405 nm) (Capinera 2008; Freas and Schultheiss 2018; Ho et al. 2017), burrowing or moving toward the location of highest light intensity.

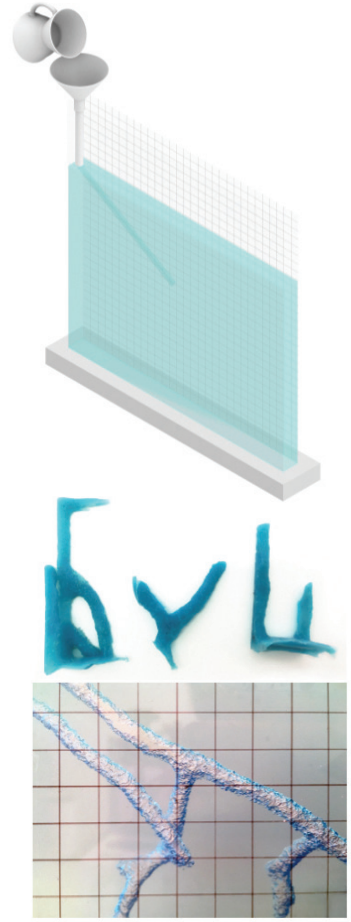
This species of ant has female workers up to 10 mm in length, with colonies that can survive up to 20 years with a viable queen (Wikipedia n.d.). They are excellent tunnel diggers and create nests that are up to 5 m deep and 1 m in diameter. This time scale and nest size are usable for building systems, and invite the possibility of having ants live in the final structure for several years with the ability to alter the structure in response to changing conditions. *P. occidentalis* was also chosen because it is a commercially available, inexpensive, and simple organism to monitor, with a limited range of simple individual behaviors that aggregate into collective construction. On a colony level, the worker ants are most likely sisters of approximately the same age (Mayer 2016) and are genetically similar (Cole and Wiernasz 1997), reinforcing the hypothesis that much of their collective development is based on responses to environmental cues rather than inherited variation.

METHODS

We conducted experiments in a clear acrylic ant arena (30 × 30 × 2.5 cm, marked with a 1 × 1 cm grid) filled with nutrient gel that ants can dig tunnels in and that provides nutrients and water. A Gearlight S100 UV LED flashlight (UV) was fixed onto a six-axis, 40 cm reach, custom robotic arm (Shi 2019) that moves the light along preprogrammed paths in the arena to test the ant's response to a moving light guide (tests 1, 2, 3a, 3b; Fig. 6). For tests 4, 5, and 6, the same arena is partitioned into two equal halves and an adjustable stationary mount was used to carry a UV flashlight in each partition (15 cm apart; Fig. 7) to test the ant's response to a stationary stimulus. A smaller control arena (16 × 14 × 3 cm), without UV, was used to test baseline ant behavior, vitality, and dig rate. All tests were run indoors, at 21°C, with normal indoor humidity. All the tests were recorded via time-lapse photography, with active ants per hour counted.



6, 7



8

6 Experiment setup for tests 1, 2, 3: UV LED fixed to 6-axis custom robot arm, moving in manually programmed path across gel-filled arena.

7 Experiment setup for tests 4, 5, 6: two UV LEDs fixed to stationary stand, 15 cm apart (1 LED per partition). Arena is partitioned into 2 equal halves.

8 Tunnels are cast in 2-part silicone, and the ant gel is reheated and reused for next test.

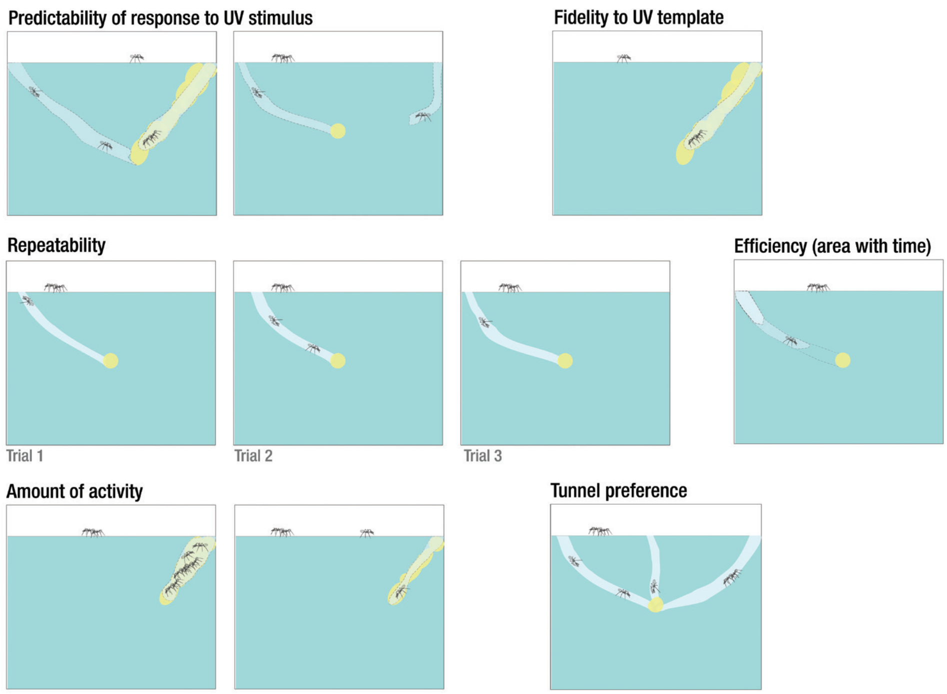
We ran eight experiments of three to seven days each, with different ant populations. With the hypothesis that the ants would always be biased to dig towards the UV, we explored the following:

- Predictability: How likely are the ants to follow the UV as a guide or target it as a goal?
- Fidelity: How precise is the digging to the UV path (guide) or target (goal)?
- Repeatability across different ant populations and numbers with identical stimulus.
- Efficiency: How much material is removed with time?
- Activity: Is dig rate affected by population size?
- Tunnel preference: Given the multiple ways that ants can dig towards the UV goal, how likely will the ants dig in the prescribed path towards the UV instead of alternative routes?

After the ants dug a significant area, we cast the complex tunnel shapes in silicone and reused the gel after casting (Fig. 8). This is of interest because fine branch structures found in nature, like ant tunnels, are often onerous or resource-intensive to fabricate, especially with subtractive technologies, so using inexpensive, self-maintaining biological fabricators offers an alternative possibility.

RESULTS

Test 0, the control, had 10 ants digging under 24-hour fluorescent light, but no UV light, for seven days. Once acclimated to the arena, the ants dug tunnels at an average rate of 2 mm per hour, although the digging was highly episodic, with periods of no digging interspersed with periods of rapid digging. The ants show a strong preference for hard edges and would dig straight down from the four corners of the enclosure before digging any branches or diagonal tunnels up. Out of 10 initial ants, only up to 4–5 ants dug at one time, and most of the digging was done by only 1–2 ants for the duration of the test. These preferences and patterns—starting tunnels at hard intersections, with most digging by a small fraction of available ants, at episodic intervals—were consistent throughout all the tests.



9

9 600 ants were observed to test the following:

(a) Predictability of response to the UV stimulus: How likely will the ants follow or target the UV?

(b) Fidelity: How precisely do the ants follow or target the UV?

(c) How repeatable are the results among different ant populations and sample sizes given identical stimulus?

(d) Efficiency: How much material is removed with time?

(e) Amount of activity: Is dig rate affected by population size or time in the arena?

(f) Tunnel preference: Given the multiple ways that ants can dig towards the UV goal, how likely will the ants dig in the prescribed path towards the UV instead of alternative routes?

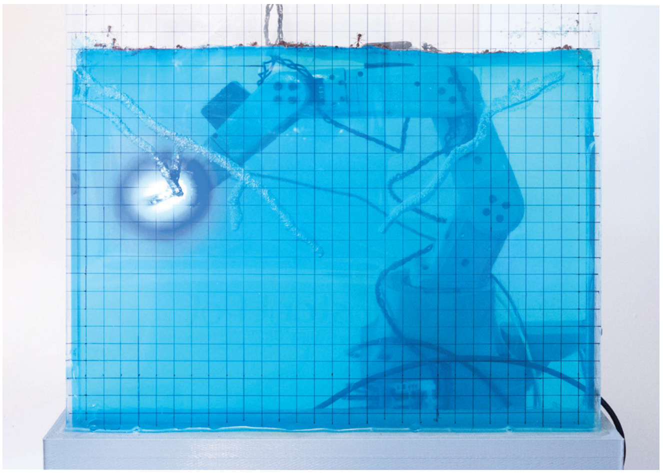
Test 1 (Fig. 10) had 30 ants and a moving UV light along a preprogrammed path on the robotic arm. The ants moved initially to the right and left front corners of the arena. When presented with moving UV light, the active ants on the right side dug the templated path with remarkable fidelity, following the path of the robot arm, including the areas of UV light dispersion (tunnel A). Some ants on the left side started a second tunnel (B), digging towards the UV light instead of alongside with it. When an additional 30 new ants were introduced (test 2), the active ants chose to develop tunnel B (UV goal), instead of tunnel A (UV guide). Again, the ants did this with high fidelity, matching vector changes in the robotic arm with their own directional change to always directly target the UV light (Fig. 11). For both tests 1 and 2, the majority of the digging was done in the first 48 hours, with rapid decrease in dig rate afterwards.

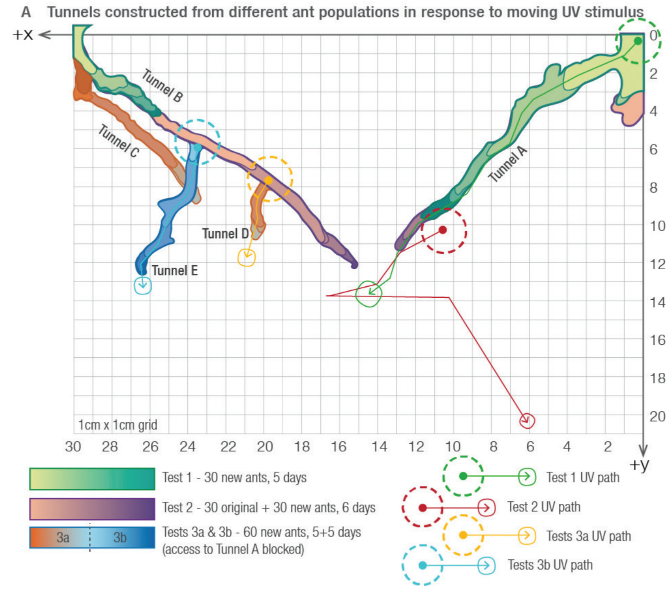
Tests 3a and 3b show how branching tunnels can be templated with a moving UV light that traces a path off of tunnel B (the entrance to tunnel A is blocked with fresh ant gel). Sixty new ants chose between following the UV light as a guide or targeting it as a goal. Test 3a had the UV light moving downward and left, off a midpoint of tunnel B. Some ants followed the UV light, creating branch tunnel D, while the majority of the diggers chose to start a new tunnel C, from the left corner towards the UV light target. The majority of the digging was done in the first three days, after which dig rate dropped dramatically. Test 3b directed another 60 ants to dig a second branch tunnel E with the UV moving from another midpoint along tunnel B; the majority of the diggers followed the UV path and dug tunnel E, instead of developing tunnel D further, with most of the digging in the first 48 hours.

Tests 4, 5, 6 (Fig. 12) show different populations of ants (15, 30, 45, 60, 75, and 90) that were presented with identical static UV light in the middle of the ant gel partition. New ants and refreshed ant gel were used for each test. Five out of the six test populations dug from the same starting point in near-identical paths towards the UV goal, regardless of total population size, number of diggers, or whether the ants were on the left or right side of the partition. In test 6, the 15 ants on the left partition dug from the opposite corner compared to the other sets, and the 75 ants in the right partition dug an additional vertical tunnel after they had completed the first expected tunnel. While this consistency is not comparable to the repeatability and precision of industrial systems, it is significant for a system based on insects with biological agency.

Two exceptions were noted, both caused by slight gel inconsistencies:

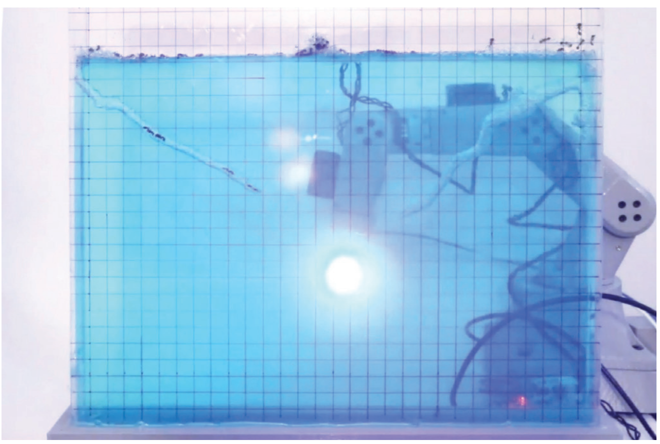
- In test 6, in the right partition (15 ants), there was a gap between the plastic divider and the ant gel, which we believe made starting a tunnel on the left easier than at the right side which was the norm for the ants before.
- In test 6, in the left partition (75 ants), the vertical tunnel was started at the discontinuous interface between the old undisturbed gel and the new gel that was poured in to replace the gel disturbed by the previous tunnel.

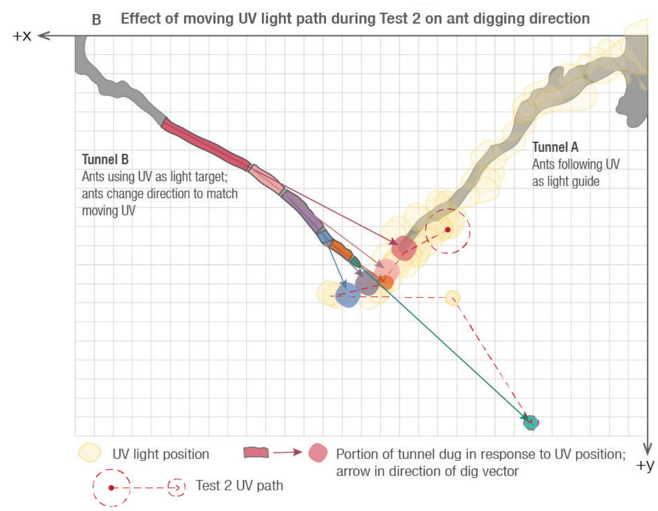




10

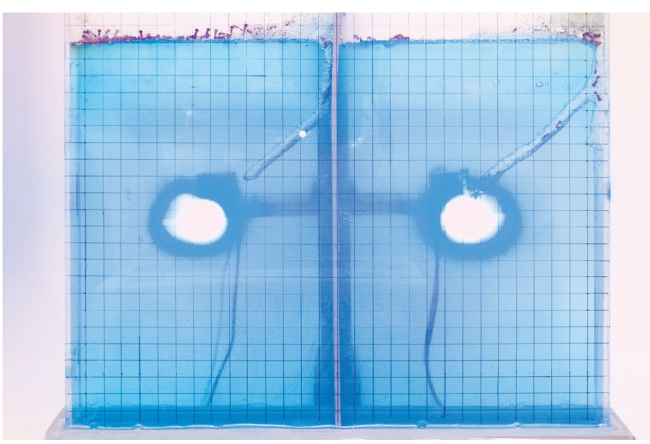
10 Tests 1, 2, 3a, 3b; Tunnels A–E dug over time, in response to moving UV guide. Color block units signify the amount of tunnel dug in 24 hours. UV guide starts in different positions (dashed circle) for tests 1, 2, 3a, 3b. End point of robot path indicated by small circle.

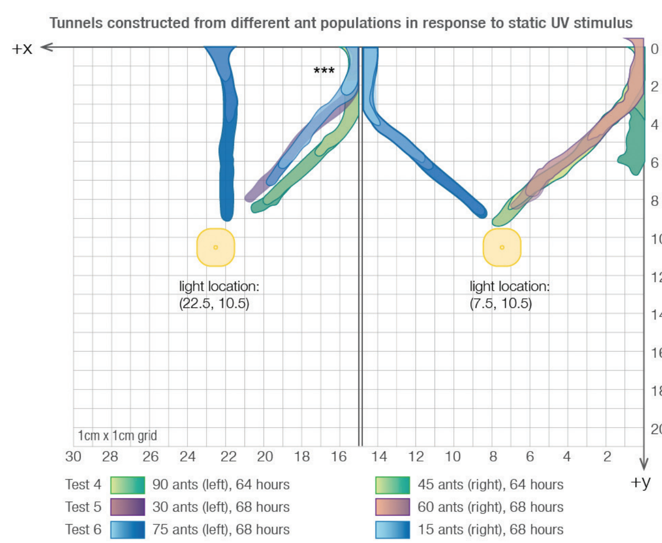




11

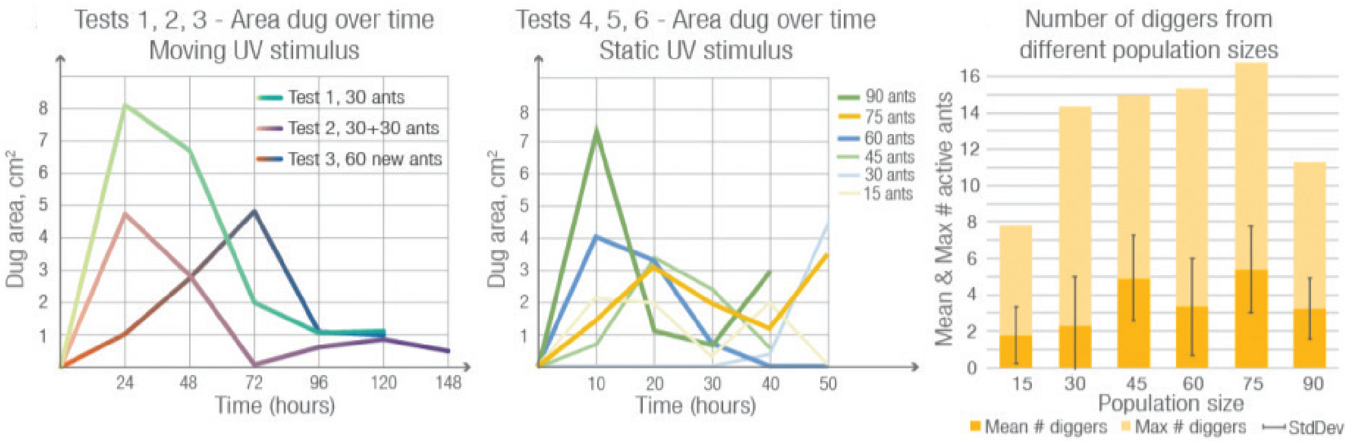
11 Development of Tunnel B during Test 2; ants change tunneling direction (as indicated by colored arrows) to match changing position of UV light path (dashed line). Color blocks indicates tunnel dug in 24 hours.





12

12 Tests 4, 5, 6: Tunnels F–L dug by different ant populations in response to stationary UV goal. Color blocks signify the amount of tunnel dug in 10 hours. Tunnels are dug by different numbers of ants using the same stimulus to test repeatability and effect of population size on dig rate.

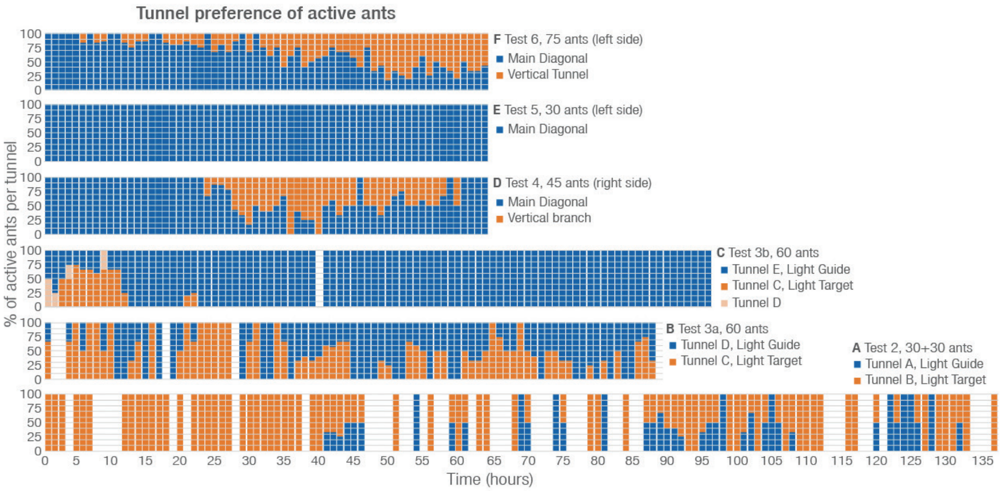


13, 14, 15

13 Area of gel dug by ants over time in response to the moving UV guide. Peak digging activity is noted to be in the first 24–72 hours of the test, after which activity rapidly drops off.

14 Area of gel dug by ants over time in response to the static UV goal. Peak digging activity is noted to be in the first 10–20 hours of the test, after which activity drops off; this is less than half the time they are active with a moving UV light. Some sample populations exhibit an increase in digging activity after 30–40 hours again to develop secondary tunnels. Intensity of digging activity is not correlated to population size.

15 Mean and maximum number of active digging ants in different population sizes of ants for tests 4, 5, 6. Increasing the population size of ants is correlated with a slight increase in maximum number of digging ants but without a significant increase in the mean number of digging ants, or an increase in dig rate.

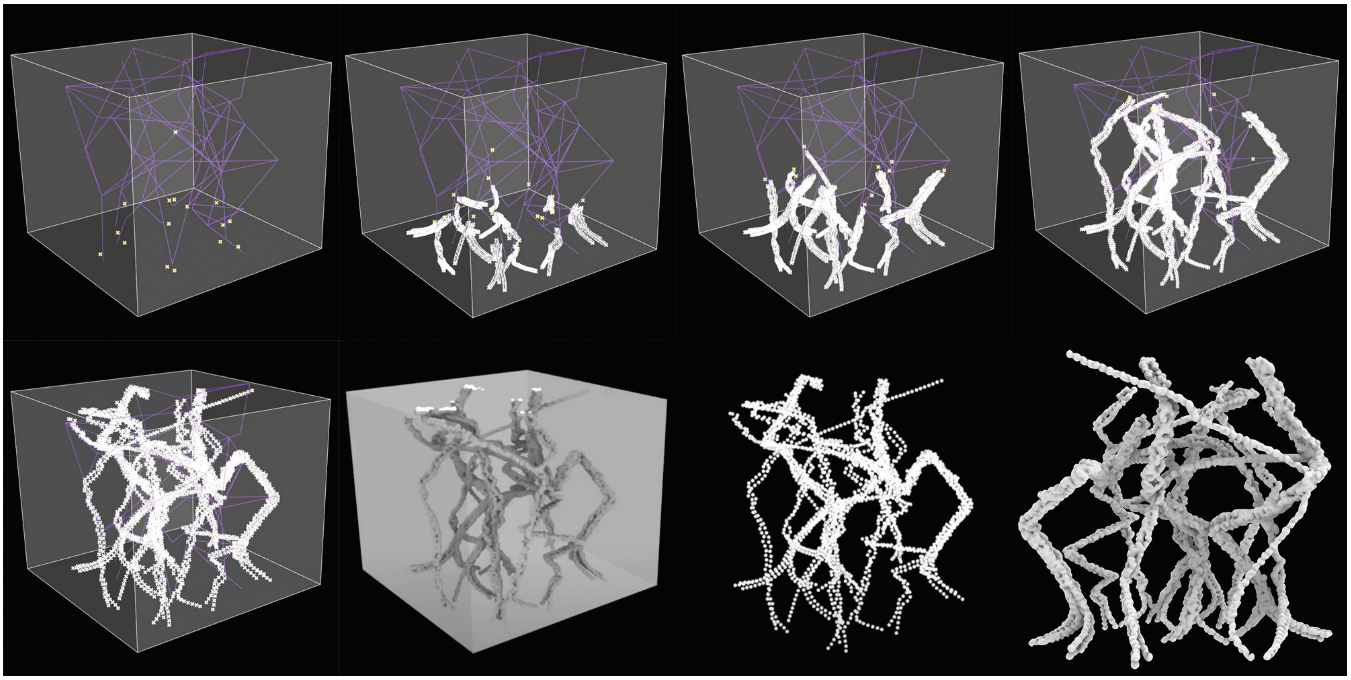


16

16 Tunnel preference of active digging ants in each test when ants dig multiple tunnels in response to same UV stimulus. Blue indicates the proportion of active ants that dug the expected tunnel in response to UV; orange indicates the proportion of active ants that dug alternative tunnels in response to UV. Test 2 shows majority of active ants dug tunnel B, using the moving UV as a target instead of as the predicted UV guide (tunnel A). Test 3a shows half the ants chose the expected branch tunnel D, while half chose to develop alternative tunnel C. Test 3b shows a majority of ants digging branch tunnel E. Test 4 shows a majority of the ants in the 45 ant partition digging the main diagonal path and some starting a small vertical branch. Test 5 shows all the ants in the 30 ant partition digging the expected diagonal. Test 6 shows majority of ants in 75 ant partition digging the main diagonal, but after it is completed, they shift towards digging a second vertical tunnel.

Population size did not seem to affect digging speed or efficiency (Figs. 13, 14), nor did it significantly alter the number of active ants digging at any time (Fig. 15). That is, smaller population sizes could dig their tunnels as fast or faster, and had proportionally more active ants, than the larger population sizes. Figure 15 shows the average and maximum number of digging ants as a function of ant population. While larger populations generally had more actively digging ants and the mean number of diggers increased with population size, doubling the number of ants did not double the number of diggers, and at 90 ants, both the maximum and mean number of diggers decreased. This indicates that arena size and environmental conditions play a large role in digging activity rather than population size.

The amount of ant activity was correlated with static or moving UV light, with ants responding more vigorously and for a longer duration to a moving UV light source than a static one. With the moving source, ants would search until they found the changing UV light direction, either matching its direction or changing course to target it. Also significant was that in addition to the UV bias, ants have other preferences when digging, like starting tunnels at the hard corners of the arena or where there were discontinuities in the gel. This was especially notable in tests 4, 5, and 6, where the UV stimulus was in the middle of the arena; instead of starting from a point with the shortest path to the UV light, the ants preferred to start at the corners downwards and then switch directions to diagonally reach the UV light. These preexisting preferences, combined



17

17 Future work using 3 dimensional gel arena with multiple moving UV light guides and multiple starting points. UV light (yellow points) follow toolpaths (purple lines) to attract ants along the tool path.

with the random local interaction of ants before collective trends can emerge, resulted in the multiple tunnels dug in response to the same UV light in numerous tests (Fig. 16).

Notable in this work is the large population of lazy ants in all the tests—up to 96% of the ants would rely on usually fewer than five hard working ants to dig the majority of the tunnels at any given time. Prior work (Aksoy and Camlitepe 2018) shows that generally at least 50% and up to 75% of a colony's ants in situ are inactive, potentially as nature's backup in case the working ants are hurt. Another potential reason for the high proportion of lazy ants in our sample sets may be that, given that we purchased these ants commercially, our sample set likely has a high proportion of older foraging ants that normally favor duties outside of the nest (and can thus be captured.) This indicates that the age range of the workers used in the experiments is important to clarify, or that a whole colony be used, in future work.

After the tests, the ant gel tunnels were successfully cast with a two-part silicone and easily removed. The gel can then be reheated and reused to create new tunnels. This suggests that casting in ant-dug tunnels would be a feasible way to subtractively form molds that would be difficult to mill. Given some of the inherent unpredictability of the tunnel paths, this would likely be a feasible manufacturing method for forms where granular detail is not critical as long as it meets higher-level goals, such as having more material cast at any point where the UV light might have been stationary or having multiple cast lines to every point the UV light was.

CONCLUSION: WHAT DO ANTS GET YOU?

Our study is a preliminary proof-of-concept that shows that ant tunneling can be consistently biased by UV light, and that this guided tunneling could be harnessed with design intent. UV biasing can be implemented with the UV light as a goal as well as a guide, with initial results showing that targeting it as a goal is more successful. Preexisting geometric features in the gel (cracks or discontinuities) or by the arena boundaries (hard interfaces) have a strong effect on where tunnels start, but eventually the ants will always be biased by the UV light, as shown by the consistent targeting of the UV stimulus in our stationary tests and the ability to prompt new branches off of old tunnels with our moving tests. Peak tunneling rates ranged from 3.3 to 8.1 cm^2 of material removed per day and was uncorrelated to the number of worker ants available but was strongly correlated to the amount of time that the workers were in the arena. The tunnels created in the ant gel can be easily cast and the gel can be melted and reused for new tunnels.

The project demonstrates that by manipulating the UV stimulus, we can provoke high-level predictable patterns of ant response, albeit with substantial low level noise. The ant gel we use provides nutrition and water and can potentially sustain the colony, while the ants inexpensively dig tunnel forms that are hard to create with existing technologies. They point towards a design approach where instead of prescriptively planning and detailing the *only* desirable outcome, the designer tunes a system towards probabilistically guaranteed outcomes that result from emergent processes with hybrid authorship. And while the system we designed cannot currently compare with the precision and consistency of an industrial fabrication system, it offers new fabrication possibilities with real-time adaptability to unexpected impedances, programmability through environmental templating, self-perpetuating sustainability, and the ability to fabricate challenging structures. This can help establish methodology for codesigning with distributed natural agents that allows for decentralized adaptive tunability during fabrication, with principles that can be applied to artificial systems of autonomous agent collectives.

This is a starting point; improvements include additional replicates of the original toolpaths and testing with larger populations, such as a whole colony or with ants of a known age. Future work also includes prototyping in 3D (to move beyond planar tunnels) and with multiple dynamic UV light sources and starting points, as in Figure 17. Finally, there is the desire to increase the precision of the UV templating as well as the scale of the structures that the ants can form to increase the feasibility of use in novel fabrication workflows.

ACKNOWLEDGMENTS

Thank you to Dr. Markus Kayser for discussing his initial tests from 2016 and to the Collective Embodied Intelligence Lab for their time.

REFERENCES

Aksoy, V., and Y. Camlitepe. 2018. “Spectral Sensitivities of Ants—A Review.” *Animal Biology* 68 (1): 55–73. https://www.doi.org/10.1163/15707563-17000119.

Capinera, J. L., ed. 2008. *Encyclopedia of Entomology*. Dordrecht: Springer Science+Business Media B.V.

Cascone, Sarah. 2014. “Artist’s Honeycomb Sculptures Made by Bees Spark Buzz.” *Artnet News*, July 7. https://news.artnet.com/exhibitions/artists-honeycomb-sculptures-made-by-bees-spark-buzz-56554.

Cole, B. J., and D. C. Wiernasz. 1997 “Inbreeding in a Lek-Mating Ant Species, *Pogonomyrmex occidentalis*.” *Behavioral Ecology and Sociobiology* 40 (2): 79–86. https://www.doi.org/10.1007/s002650050318.

Freas, C., and P. Schultheiss. 2018. “How to Navigate in Different Environments and Situations: Lessons From Ants.” *Frontiers in Psychology* 9: 841.

Gilbert, Charlie, T.-C Tang, W. Ott, B. A. Dorr, W. M. Shaw, G. L. Sun, T. K. Lu, T. Ellis. 2021. "Living Materials with Programmable Functionalities Grown from Engineered Microbial Co-Cultures.” *Nature Materials* 20 (January): 691-700. https://doi.org/10.1038/s41563-020-00857-5.

Gordon, D. M. 2002. “The Regulation of Foraging Activity in Red Harvester Ant Colonies.” *American Naturalist* 159 (5): 509–518. https://www.doi.org/10.1086/339461.

Ho, P. H. C., C. Smuts, M. A. R. Kayser, and J. Hernandez. 2017. “Ant-Based Modeling: Agent-Based City Simulation with Ants.” In *CHI EA '17 [Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems]*, Denver, CO, 6–11 May 2017, edited by Gloria Mark and Susan Fussell, 475–475. Association for Computing Machinery.

Kayser, Markus. 2018. “Towards Swarm-Based Design: Distributed and Materially-Tunable Digital Fabrication Across Scales.” PhD thesis, Massachusetts Institute of Technology.

Mayer, J. 2016. “Ants.” *General Entomology*. North Carolina State University. March 25. https://projects.ncsu.edu/cals/course/ent425/library/tutorials/behavior/ants.html.

Nguyen, P. Q., N.-M. Dorval Courchesne, A. Duraj-Thatte, P. Praveschotinunt, N. S. Joshi. 2018. “Engineered Living Materials: Prospects and Challenges for Using Biological Systems to Direct the Assembly of Smart Materials.” *Advanced Matter* 30 (19): Article 1704847. https://doi.org/10.1002/adma.201704847.

Oxman, Neri, Jared Laucks, Markus Kayser, Jorge Duro-Royo, and Carlos Uribe. 2014. “Silk Pavilion: A Case Study in Fibre-Based Digital Fabrication.” In *Fabricate: Negotiating Design & Making*, edited by Fabio Gramazio, Matthias Kohler, and Silke Langenberg, 248–255. Zurich: gta Publishers.

Shi, Kowin. 2019. *SkookumAsFrig/Mini_6DOF_Arm*. Python. https://github.com/SkookumAsFrig/Mini_6DOF_Arm.

Walsh, Nicole. 2015. “Meet the Woman Making Art with Termites.” *Vice*, August 7. https://www.vice.com/en/article/8qvmwz/meet-the-woman-making-art-with-termites.

Wikipedia. n.d. “Pogonomyrmex Occidentalis.” Article. Last modified January 3, 2021. https://en.wikipedia.org/wiki/Pogonomyrmex_occidentalis.

IMAGE CREDITS

Figure 3: © *Silk Pavilion II*, Neri Oxman & the Mediated Matter Group, 2020. The Museum of Modern Art, New York, photographed by Denis Doorly.

All other drawings and images by the authors.

Andrea Ling is an architect, artist, and biodesigner at ETH Zurich. She holds an MS from the MIT Media Lab and an MArch from the University of Waterloo. Her research is on how the critical application of biologically mediated design processes can move society away from exploitative systems of production to regenerative ones.

Mahshid Moghadasi is a MS student in Matter, Design, Computation at Cornell and research associate at JSLab. She holds a BArch and MS in architectural technology from University of Tehran. Her research is focused on robotic assemblies in architecture.

Kowin Shi is an automation hardware engineer at Uber ATG. He has an MEng in ECE and BS in mechanical engineering from Cornell. His current work focuses on autonomous car delivery.

Junghsien Wei is an MEng student in electrical and computer engineering at Cornell. His research is on autonomous control in robotics, focusing on drones, autonomous cars, and blimp delivery.

Kirstin Petersen PhD explores the design of bio-inspired robot collectives and their natural counterparts. She leads the Collective Embodied Intelligence Lab at Cornell University in electrical and computer engineering. She did her PhD at Harvard University and the Wyss Institute for Biologically Inspired Engineering and a postdoc at the Max Planck Institute for Intelligent Systems,