

# Collective Construction of Ramification Patterns in Resistive Media

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## 1 Introduction

Paths and trails are generally useful to intelligent agents, especially in environments that are energy-intensive to explore. In many settings, the environment resists agent navigation, but in a way that is reduced *by* navigation so that the next time an agent travels on that path, their locomotion is more efficient. An example with transient dynamics are chevron formations used by birds where followers draft behind the leader to conserve energy. In rugged environments, semi-permanent game trails are formed by animals and used by many species. Here, we focus on static resistive environments, where the medium does not evolve in time other than when modified by the agents.

Termites are an especially impressive example of collective trail formation, in the form of three-dimensional underground nests and tunnels. Termites are not able to sense their food source (wood) while constructing foraging tunnels: they must dig blindly and hope to stumble upon their targets. Termites have evolved a plethora of reactive strategies for foraging tunnel construction, to the point where the spatial distribution of their foraging tunnels is tuned optimally to the distribution of food in the environment Lee et al. [2007], without any centralized strategy or construction foreman. We are particularly interested in strategies for excavation of ramified (branching) networks: what are the cues for tunnel branching, and how do biological systems tune the spatial distribution of their tunnels?

We hypothesize that in *C. formosanus* termites, the shape of the tunnel tip serves as a local stigmergic cue that induces branching through automatic reactions determined by termite morphology.

The interplay between the crowding of termite workers and the stigmergically created boundaries that are the tunnel walls is difficult to assess directly. How much of an individual excavator’s decision on where to focus digging is due to the cognition of the insect and how much emerges due to crowding which forces a narrow range of excavation sites on the individual? To investigate the role of simple crowding in governing tunnel branching, we created a system of simple robots with no information processing ability. They simply react to a stigmergic system and each other.

In this work we compare these two systems and show that the paths and tunnels encode information that can be accessed by asynchronous agents. Two inextricably linked cues generally govern construction of branching paths or tunnels: the spatio-temporal evolution of crowding events, and the geometric structure of the tunnel tip. Work in ants has indicated that both agent-agent and agent-environment interactions influence emergent construction Prasath et al. [2022], Toffin et al. [2009], but has largely focused on synchronous dynamics of the agents and the environment. In this work, we show that tunnel widening and shape evolution, cued by crowding events, can cue tunnel branching even after the crowding event has resolved. This indicates that stigmergic mechanisms are in use and information is being passed through the environment without requiring tactile or pheromonal interactions between termites. We verify this finding via experiments with artificial plowing agents. Finally, we explore implications of these results for distributed and network-free approaches to collective robotic construction.

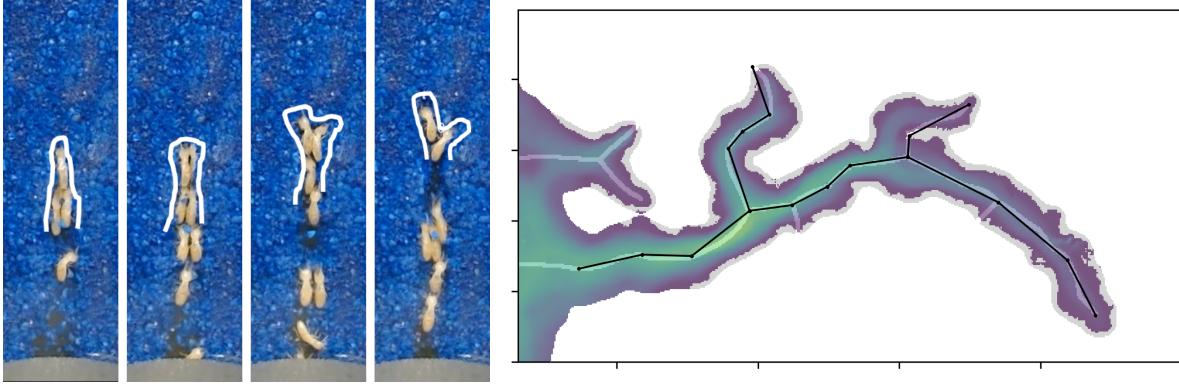


Figure 1: (Left) Four screenshots from a video of *C. formosanus* termites, with time progressing left to right. The white outlines demonstrate how the tunnel tip profile can change in the lead-up to a branching event. (Right) Automatically generated heat map of termite occupancy over 1.5 hours. The occupancy map is labelled with the automatically inferred skeletonization (white) and the discrete network topology (black).

## 2 Related Work

Stigmergy Grassé [1959] is an indirect mode of communication between agents, where actions taken by one agent affect the actions of subsequent agents visiting that location. In termites, nest and gallery building has been studied extensively and modelled assuming the process is guided by pheromone stigmergy Bonabeau et al. [1998], Deneubourg and Franks [1995], Ladley and Bullock [2005], O’toole et al. [1999], but more recent work indicates that pheromone labelling plays a smaller role in foraging tunnel construction than the interplay between agent-agent interactions and tunnel geometry Bardunias and Su [2010]. This work defines a “digging pressure” in the context of termites, caused by the active orientation of tunnelling behaviors away from the mouth of the tunnel via dead reckoning Bardunias and Su [2009]. Here, we extend this line of work to define specific geometric cues and conditions for tunnel branching events that are based purely on tactile interactions.

Collective construction behaviors in ants have also been widely studied; one line of work has explored the mechanisms used by ants to transition from a convex nest cavity to a ramified tunnel structure Toffin et al. [2009]. The authors of Prasath et al. [2022] extend this work, and additionally use a robotic platform to demonstrate reactive strategies for collective escape. However, these works focus on agent density and inter-agent cooperation as the primary cues for excavation behaviors. Here, we focus on the next stage of collective excavation: what are the cues for tunnel branching, and how have biological systems evolved these cues and reactions to tune the spatial distribution of their tunnels? We also explore asynchronous methods of coordination since as agents disperse through a network of tunnels, inter-agent interactions become rare and often a single agent is excavating at a time.

Termite excavation strategies appear to be widely variable but reliant mainly on local cues of tunnel crowding and geometry. A study of three different termite species found that two related species transport sand in the same way using mandibles, but different tunnel geometry emerges from different probabilities of choosing between excavating the sidewall to make a new branch or waiting for clearance to extend the current tunnel. A third species independently evolved different building rules, namely, a bucket brigade that can excavate a crowded tunnel, that are capable of creating similar tunnel geometries to a mandible-based strategy. Mizumoto et al. [2020].

Work in ants has indicated that confinement and crowding has a strong influence on ant behavior and motility Gravish et al. [2015], and that the emergent collective dynamics can be modelled by a physical model of glass dynamics. Ramified structures are common in nature, from river watersheds to tree roots and branches. A branching network is in many cases the optimal structure resulting from a pressure to search for resources or find a minimum-energy path, and can be formed through distributed mechanisms. In Devauchelle et al. [2012], the authors define a diffusive field model and Poisson process that explain the formation of ramified stream networks and has good agreement with the actual geometry of stream networks.

Our work lays the foundation for similar physical models of ramification pattern construction, since we show that system information processing is mediated more by the environment than by per-agent computation.

## 3 Methods

### 3.1 Termites

Termites were collected from three *Coptotermes formosanus* colonies, and stored at  $27 \pm 2^\circ$  Celsius in plastic boxes with thin, moist wood chips for no more than 30 days prior to experimentation. The experimental arenas are similar to those used by Lee et al. Lee et al. [2008]. Each arena consists of two layers of clear acrylic, top and bottom ( $13.5\text{cm} \times 4\text{cm} \times 5\text{mm}$ ), between which is a 2mm pad of blue aquarium sand contained by a 2mm gasket. The sand was moistened with deionized water  $\approx 7\%$  by sand weight.

To observe termite behavior when constructing exploratory or foraging tunnels, we placed approximately 40 termites into a pre-dug “nest cavity” in the center of each arena. The nest cavity has distinct corner features pointing left and right to cue termites to dig. The termites were allowed to dig for approximately three hours while being filmed by a camera with  $1920 \times 1080$  resolution.

The termite videos were then segmented with a hue-saturation-value (HSV) filter, the bounds of which were evaluated on ten random frames in each video for accuracy and consistency.

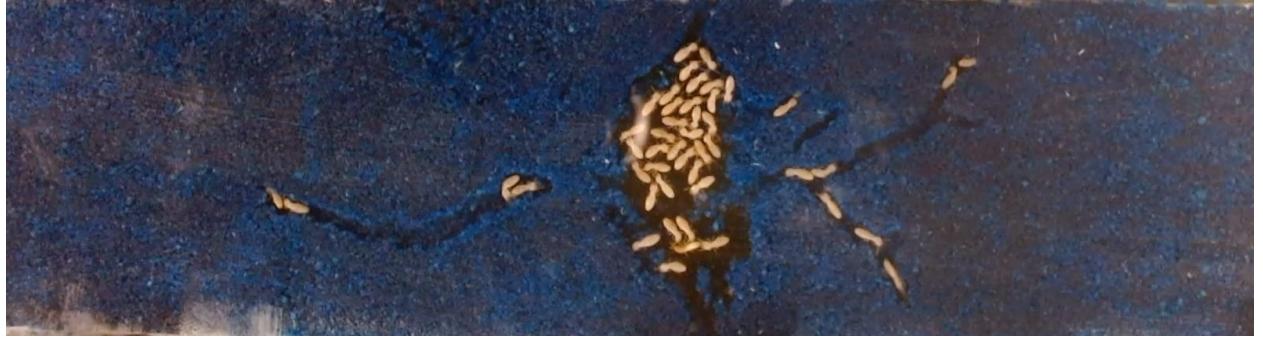


Figure 2: Arena used to capture termite data.

### 3.2 Artificial Collective

As a first step toward principled design of tunnelling or trail-making robotic systems, we investigate the emergent behaviors of a collective that is traversing a homogenous granular environment. We designed a simple experimental apparatus to demonstrate fundamental synchronous and asynchronous interactions involved in mechanically-mediated trail formation and excavation.

The agents, which we will refer to as Pucks, consist of a battery, motor, and switch in the center of a circular Puck. The walls of the Puck are designed to facilitate movement and plowing through sand when the motor causes vibrational locomotion. See Fig. 4 for details of the Puck assembly and functioning.

The experimental arena consists of a 36 inch by 24 inch board, with walls, covered with sand to a depth of 10mm and tilted at 15 degrees, with a single overhead camera. The angle of the arena was chosen to produce approximately constant velocity motion in the direction of the tilt when plowing through uniform sand. Video was calibrated with a printed checkerboard and openCV routines.

In the case of Pucks plowing through sand, the first Puck that plows creates a path that is energetically favorable for the Pucks that follow. The following Pucks are then able to accelerate, since the drag force that balances the gravitational force has been reduced. Inevitably, the followers catch up to the “leader” and make direct physical contact in a clustering stage. Some force is transmitted to the PuckBots on the frontier of the cluster, but since a position directly behind another puckbot is an unstable equilibrium, the followers begin to rotate around the leaders and move outward from the primary vector of motion. The tunnel widens, and in many cases, a branch forms as one of the queued bots begins to plow its own path in the sidewall.

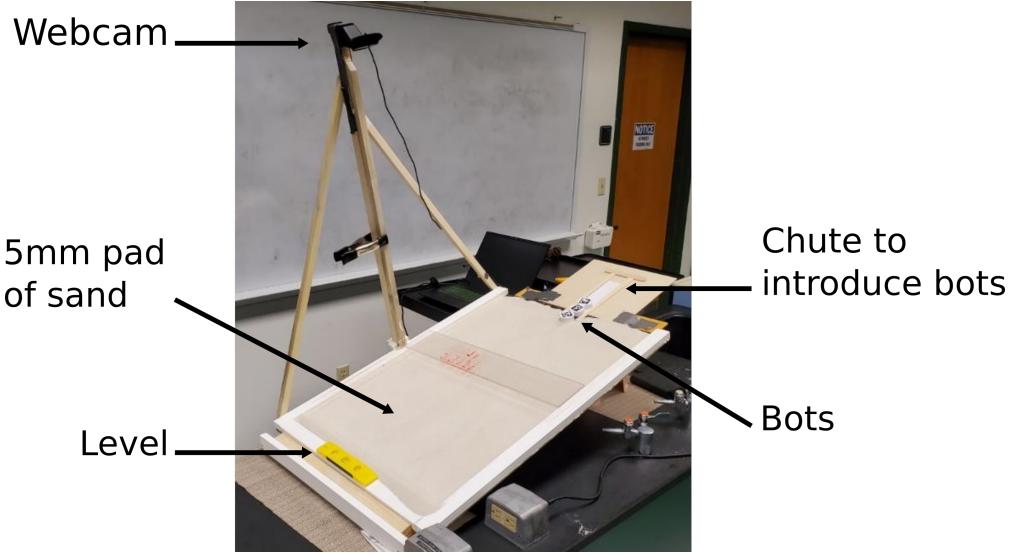


Figure 3: Experimental apparatus for collecting data on the artificial plowing agents (Pucks). The sand pad is tilted at 15 degrees from the horizontal.

We performed two experiments, one to characterize the ramification patterns produced by collectives of  $N$  Pucks as we vary  $N$ , and one to characterize the statistics of branching events as we vary the relative angle of a “follower” Puck in a pre-plowed path.

### 3.3 Geometry and Occupancy Analysis

Binary masks are generated for each system, using the AprilTags and known dimensions of the Pucks, or the HSV mask of the termites. These masks are used directly for studies of occupancy in the tunnels, and are accumulated to approximate the total excavated area. Once we have accumulated the mask of the entire tunnel structure, we use openCV’s skeletonization algorithm to skeletonize the tunnel for analysis of its geometry. A combination of automatic and manual labelling is used to approximate the tunnel skeleton as a tree of line segments, and these line segments are used to compute the length of each tunnel segment between branches, as well as the characteristic angle of each branch.

## 4 The Effect of Crowding

### 4.1 Tunnel Geometry Distributions

First, we characterize the emergent geometry of tunnels constructed by termites and Pucks.

By summing the lengths of segments between branch points, we are able to estimate the arc-lengths between branches and thus the spatial frequency distribution of the branch events. See Figure 5 for an example, with the tunnel arc-lengths labelled in terms of bodylengths.

Table 1: Branch Frequency Data

Number of Pucks	Number of Trials	Number of Branches
1	52	0
2	35	0
3	33	35

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Figure 4: Top left: disassembled Puck with scale. Top right: CAD design of the Puck housing. Bottom: side view of two Pucks plowing to the right, through a 5mm sand pad.

Table 1: Branch Frequency Data (Continued)

6	31	50
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From Table 1, we can see that at least three Pucks are required for branching, and six Pucks create the expected fractal pattern where the large group splits into smaller subgroups, that then branch again when they consist of three or more Pucks.

## 4.2 Crowding and Shape Evolution

From the skeletonization algorithm, we obtain a metric of the tunnel geometry, since each point on the tunnel skeleton is equidistant to two or more walls of the tunnel. We selected 18 branches from the dataset that demonstrated a clear bifurcation at least five bodylengths away from the initial nest cavity, and occurred at least 15 minutes after the start of the experiment. The results of this analysis are seen in Figure 7. The lower mean and smaller variance at the tunnel tip 15 minutes before a branch event shows a tendency for narrow tunnel tips during “normal” foraging tunnel construction, while widening at the tunnel tip is more apparent immediately before branching events.

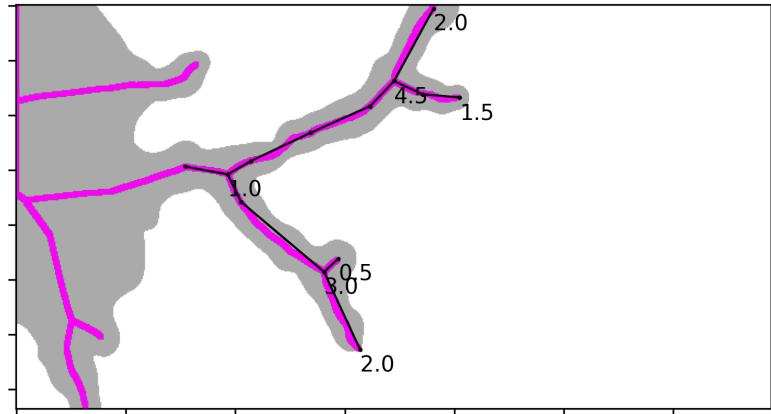


Figure 5: An example ramification pattern formed by the swept area of the termites, along with the skeletonization and estimation of arc-lengths between branch points, in rounded body lengths. This figure was generated from the right hand side of Fig. 2.

### 4.3 Density Correlations

## 5 The Effect of Stigmergic Signals

### 5.1 Stigmergy in Termites

### 5.2 Stigmergy in Artificial Collectives

To further investigate how the interplay between digging pressure and stigmergic signal strength generates branching events, we performed a set of experiments where we pre-plowed a path for an Puck at varying angles on the sandy slope. We show statistically significant effects of the angle of the pre-plowed path, indicating that there is a highly nondeterministic region of the physical system’s phase space, in between two highly deterministic regions. This is interesting in the context of robotic collectives, because it indicates that we can engineer robotic plowing or tunnelling systems with tunable behavior in the intermediate range, while behavior is well-defined in other parts of the system design space.

When the pre-plowed path is nearly straight down the hill, an additional Puck added into the path will stay within the lower-resistance path for the entire trial. But when the pre-plowed path becomes “shallower,” requiring the Puck to turn from its natural downhill heading to remain in the path, there reaches a point where the Puck always breaks out of the pre-plowed path immediately to continue straight down the slope. Between these two extremes lies a regime where the Puck remains in the pre-plowed path for a time, then breaks out by plowing through the pre-existing berm. The data and model presented here are a first step toward understanding the robophysics of this interaction, toward the goal of engineering multi-robot systems that can controllably tune their collective trail formation ramification patterns.

Table 2 shows the measured median distance and time taken until breakout occurred, including all datapoints, even those that reached the end of the pre-plowed tunnel without breakout (so the distance travelled was logged as the length of the tunnel, generally between 11 and 12 bodylengths, and the time travelled was logged as the time the Puck reached the end of the pre-plowed tunnel). The raw data is shown in Fig. 10.

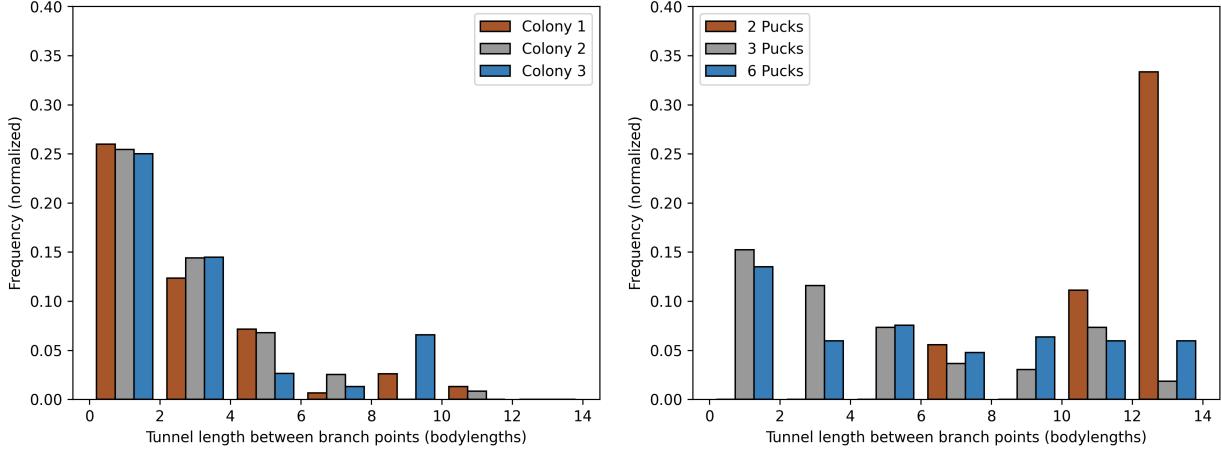


Figure 6: Length of tunnels between branch points.

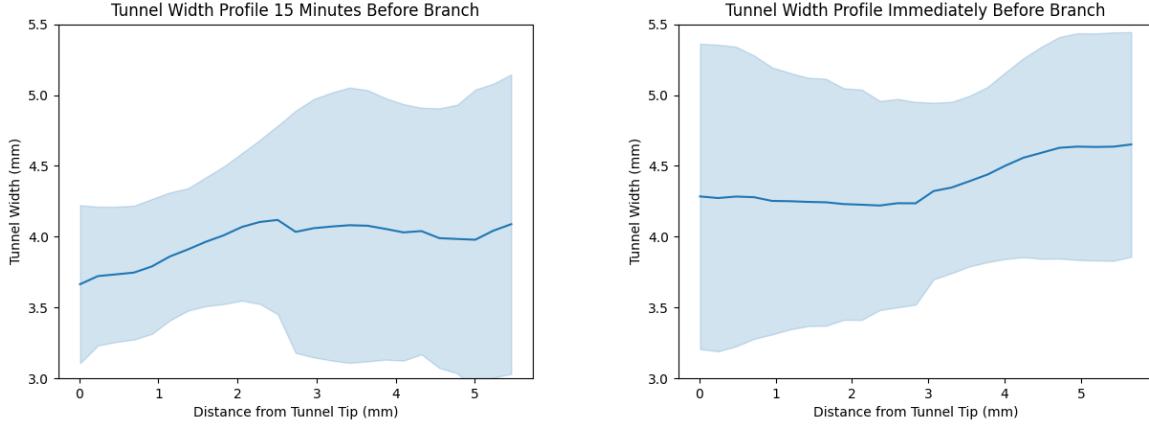


Figure 7: Tunnel mean width and variance, 15 minutes before branch on left, and immediately before branch on right.

Table 2: Median values for all trials of each treatment

Treatment	Travel Distance (Bodylengths)	Travel Time (seconds)
60	1.1	30.0
65	3.9	177.0
70	6.9	265.0
75	12.4	243.0
80	11.5	286.5

Qualitatively, as we vary the angle of the pre-plowed path, the distance travelled increases gradually, while the time before breakout or trial termination remains relatively constant. This is caused by the reduced stigmergic signal (resistance) as the angle of the pre-plowed tunnel increases - less of the Puck's potential and electric energy is being absorbed by the interaction with the environment, and the Puck has a higher velocity. This higher velocity may also play a role in inducing branching events, so these results indicate that further study is warranted using velocity-controlled robots on a flat surface, and that doing so

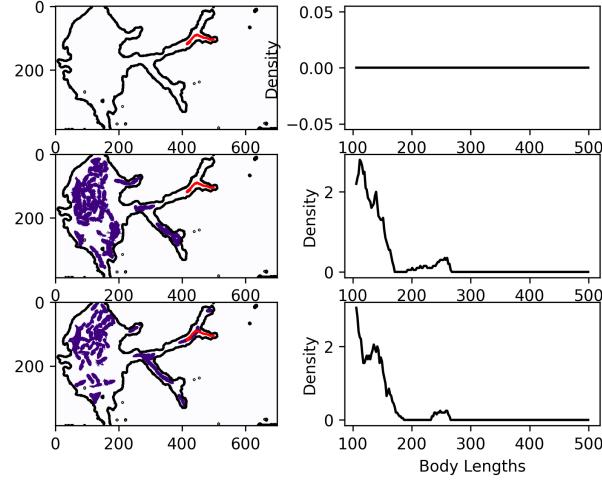


Figure 8: Snapshots of termite occupancy and estimated 1D agent density along the red line.



Figure 9: Close-up photograph of the head of a termite, demonstrating how the antennae are capable of deforming to the tunnel tip shape.

can improve the statistical separability of stigmergic signals.

To test the separation between trials, we performed a nonparametric Mann-Whitney U test between each pair of treatments, and resulting p-values are seen in Tables 3 and 4.

Table 3: P-values of independent Mann-Whitney U test with unequal sample sizes for each pair of breakout distance distributions.

<b>Separated From?</b>	60	65	70	75
65	0.002			
70		0.226		
75			0.003	
80				0.210

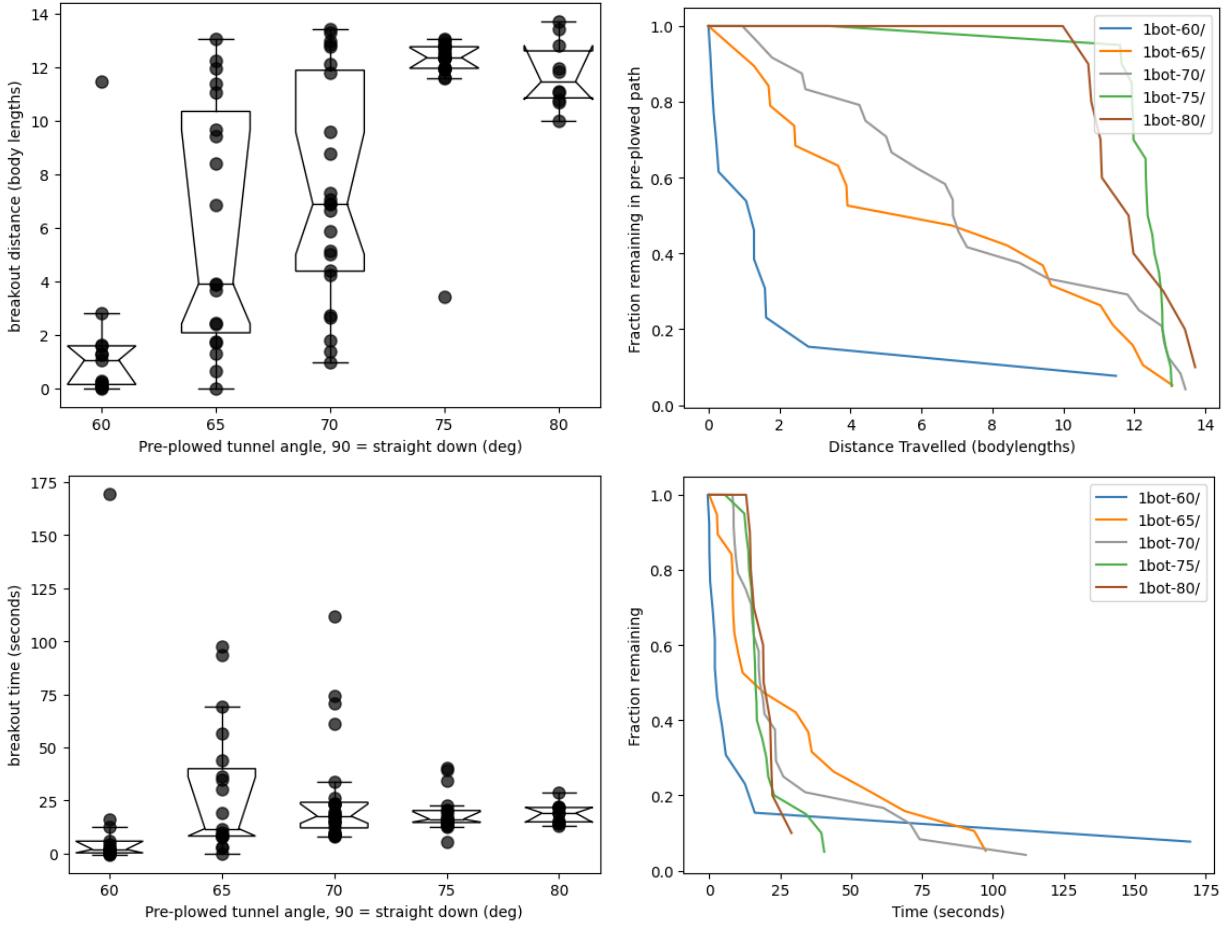


Figure 10: Raw data for stigmergic Puck experiments.

Table 4: P-values of independent Mann-Whitney U test with unequal sample sizes for each pair of breakout time distributions.

Separated from?	60	65	70	75
65	0.007			
70		0.471		
75			0.663	
80				0.567

Since we are performing a family of tests on the same underlying system, we apply the Bonferroni correction, to control the family-wise error rate (FWER). To have less than a 5% FWER, we use  $p < \alpha/n$ , where  $\alpha = 0.05$  and  $n$  is the number of pairwise comparisons, in our case,  $n = 4$  for four pairwise comparisons. Therefore, we interpret breakout distance/time distributions to be significantly separated if the p-value of their associated test is less than 0.0125.

Under this correction, we see that when we consider distance travelled, tracks at 60 degrees are distinguishable from tracks at 65 degrees; at 60 degrees, we saw bots stay in the track in all trials. With the data we collected, 65 degree and 70 degree tracks are not distinguishable from each other, but both are distinguishable from the regime at 75 and 80 degrees tracks where the bots break out of the track nearly immediately. When looking only at time travelled, the only distinguishable case is the immediate branch

case at 60 degrees: the lower resistance berm leads to faster Pucks and a compression of the breakout time distributions.

The median breakout distance of each treatment is shown, with bold lines indicating statistically indistinguishable distributions. In effect, we have three regimes: immediately break out, never break out, and a third regime between these that is much more stochastic and potentially tunable.

## 6 Discussion

With our artificial collective of Pucks, we showed that in static, granular environments no explicit on-board intelligence, or even sensing, is required to create ramification patterns. We show physical invariants involving Puck speed and the resistivity of the environment, with promising implications for robotic systems. As termites are capable of sensing nearby agents and tunnel geometry, we show that tunnel width and shape encode past information about termite occupancy, and enable sophisticated construction of tunnels in a completely distributed and pheromone-free manner.

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