Supplementary Material

1 CELLULAR AUTOMATA MODEL

The Cellular Automata (CA) model consists of a rectangular lattice with each cell taking one of four possible states at each simulation time step: soil (gold), empty or excavated soil (white), ascending excavator (gray), and descending excavator(orange). See figure S1. The dark cells represent the home area where CA ants start every trip and rest, similar to the robotic experiment setup (figure 1). At each time step, a CA ant located in the tunnel can move one cell forward if the cell is unoccupied until it gets to the digging site (gold) to excavate. If there is jamming and no adjacent cell is empty, a descending ant "gives up" and exits the tunnel with a probability P_r (the reversal probability).

To find the optimal reversal probabilities as a function of tunnel length, we conduct an exhaustive search on the tunnel length versus reversal probabilities for the range of values that give the maximum rate of excavated pellets. For each experiment trial, we fix the tunnel length and count how many grams of pellets (or successful trips) the CA ants deposit per simulation time. This gives the heatmap plot shown in figure 3A.

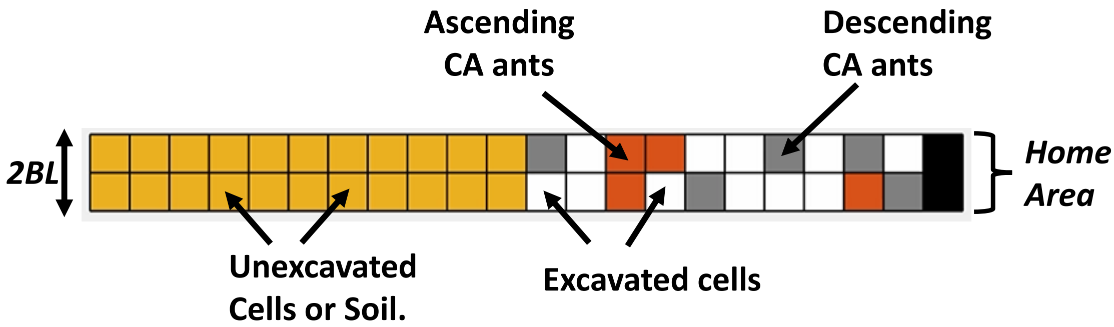

Figure S1. Schematic showing the main components of the CA model. Cell colors denote soil (gold), empty/excavated cells (white), ants moving toward the excavation site (gray), and ants exiting the tunnel (orange).

2 ROBOT ODOMETRY MODEL

Consider a differential drive mobile robot shown in figure S2 below. The robot starts from a known initial configuration X_{t-1}, and the right and left wheels move respective distances Δs_r and Δs_l and the robot arrives at a new configuration X_t. The estimate of robot's new configuration can be derived as follows. Let $\Delta\theta$ be the change in angle, and Δs be the distance travelled by the robot between time interval $t-1$ and t. Assume the robot is travelling on a circular arc of constant radius R. Therefore:

$$\Delta s_l = R\Delta\theta; \qquad \Delta s_r = (R + 2L)\Delta\theta; \qquad \Delta s = (R + L)\Delta\theta \tag{S1}$$

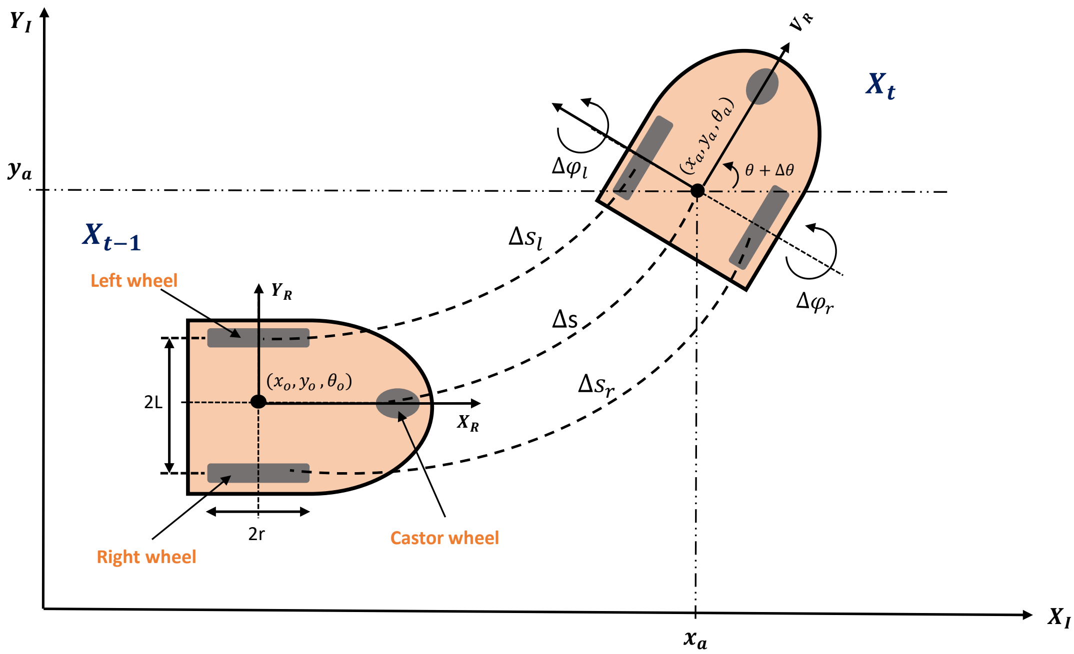

Figure S2. Model of a differential drive mobile robot.

Expressing Δs and $\Delta\theta$, in terms of Δs_l and Δs_r, we have:

$$\Delta s = \frac{\Delta s_l + \Delta s_r}{2}; \qquad \Delta\theta = \frac{\Delta s_r - \Delta s_l}{2L} \tag{S2}$$

To compute the position change in global coordinates, we assume the motion of the robot within the time interval is small such that Δs can be approximated with a straight line. Thus, we have:

$$\Delta x = \Delta s \cos(\theta + \Delta\theta/2); \qquad \Delta y = \Delta s \sin(\theta + \Delta\theta/2) \tag{S3}$$

Thus, new robot's configuration can be written more compactly as follows:

$$X_t = f(x, y, \theta, \Delta s_r, \Delta s_r) = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} + \begin{bmatrix} \cos\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right) & 0 \\ \sin\left(\theta + \frac{\Delta s_r - \Delta s_l}{4L}\right) & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta s \\ \Delta\theta \end{bmatrix} \tag{S4}$$

To express linear, Δs, and angular, $\Delta\theta$, displacements of the robot in terms of incremental wheel encoders' data ($odometry$), we have:

$$\begin{aligned} \Delta s &= \frac{r}{2}(\Delta\phi_r + \Delta\phi_l) \\ \Delta\theta &= \frac{r}{2L}(\Delta\phi_r - \Delta\phi_l) \end{aligned} \tag{S5}$$

Where $\Delta\phi_r$ and $\Delta\phi_l$ are the number of wheel rotations measured from the right and left encoders respectively during the sampling time, say T_s.

3 SUPPLEMENTARY VIDEOS

Related movies showing a demonstration of the Adaptive Protocol in our multi-robot collective excavation setup can be found on this youtube link.