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SPECIAL FEATURE: ORIGINAL ARTICLE

Robophysical study of excavation in confined environments

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Abstract Soil-dwelling social insects build complex nests. Nest excavation is performed by multiple animals simultaneously and is governed by local interactions of the workers with other nest-mates and their surroundings. To investigate collective confined excavation challenges, we built groups of robotic excavators capable of performing hours of autonomous tunnel excavation in a model cohesive granular medium. Excavator behavior was governed by a simple set of rules triggered by interactions with the surrounding environment and other robots. The rate of tunnel growth and energetic costs of excavation were measured for groups of different numbers operating in wide and narrow tunnels. To extend the results to systems with large numbers of robots, we developed a cellular automata model. Experiments and simulations showed that in sufficiently wide tunnels an increase in the size of the excavating group increased the excavation rates without a significant increase in the energy consumption per robot. A decrease in the tunnel width resulted in a decrease in the excavation rates and increase in the energetic costs of excavation. We attribute this effect to the emergence of multiple time-consuming interactions (clogs) among excavating robots in the confined spaces. Although in all situations clogs were resolvable, clog resolution took longer in the systems with larger number of robots and narrower tunnels. We expect that our robotic system can be used to investigate the behavior of social insects in confined spaces as well as inspire more sophisticated search-and-rescue robotics.

Keywords Robots · Ants · Confined spaces · Autonomous excavators

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1 Introduction

The ecological success of social insects like termites and ants is overwhelming [1]. These animals live in large societies often composed of millions of individuals [2]. The nests of social insects are complex and often considered as an extended phenotype [3] of the colony. The complexity of the nest reflects the need of the colony for space to perform social functions including mating, brood care, communication, food sharing, provision and defense [3, 4]. Nest construction proceeds through the collective performance of multiple workers [5], and is carried out through the interactions of excavators with the environment and other excavators, typically in the absence of centralized control [6]. The outcome of the collective construction is, thus, a composite of the efforts of the individual workers.

In many situations, like collective foraging, brood care or nest relocation [7], an increase in the number of workers reduces the amount of work performed by a single animal and, presumably, the cost of allective task for participating workers. However, it is unclear if these predictions are valid for subterranean nest construction by social insects.

For example, *S. invicta* fire ants build their nests in conditions of rough terrain, deprived vision, high locomotion speeds, confined environment and crowdedness [8]. These nests are built through the excavation and transport of soil loads by workers operating in narrow interconnected tunnels and chambers [9] prone to clogging. The latter

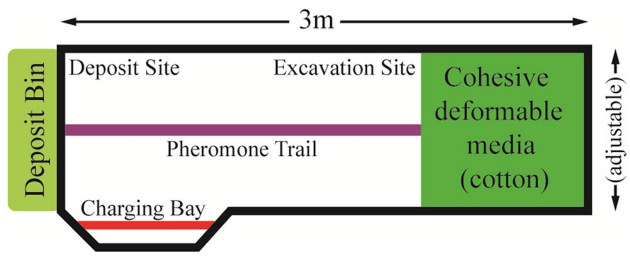

Fig. 1 Schematic of a table top test bed with adjustable tunnel walls

becomes especially important when the number of animals working in the narrow tunnels increases. Although some experimental work has been conducted to address the costs and benefits of subterranean nest excavations [10], the challenges of collective excavations in such conditions are yet to be understood.

We hypothesize that an important challenge for animals in confined spaces is the establishment of steady traffic flow. Following [11], we posit that the role of clogging and nearly jammed states of flow cannot be ignored. Taking a robophysical approach (discovery of physics principles using simple robotic systems) [12], we reveal principles governing collective excavation in confined spaces through robotic and experimentally validated simulated diggers capable of continuous collective autonomous excavation. The effect of group size on the costs and benefits of excavation is non-trivial and is influenced by the width of the tunnel. The results of the models demonstrate the importance and the need for clog mitigation strategies during confined behaviors.

2 Experimental setup

2.1 Test bed design

A small group of robots was designed to operate within a horizontal tunnel (Fig. 1) featuring a charging bay and a media deposition area. The tunnel was partially filled with a cohesive deformable granular medium (colored cotton balls). The width of the tunnel could be adjusted by changing the distance between the wooden walls. A visual guide (fluorescent tape) mimicking ant pheromone trail was secured to the tunnel floor to assist robots with navigation between the cohesive media and the deposit area. The charging station was also marked with a unique visual cue.

2.2 Robot design

Robophysical experiments are crucial for elucidating a basic set of behaviors sufficient for successful operation of a multi-robot system in confined spaces, validating the

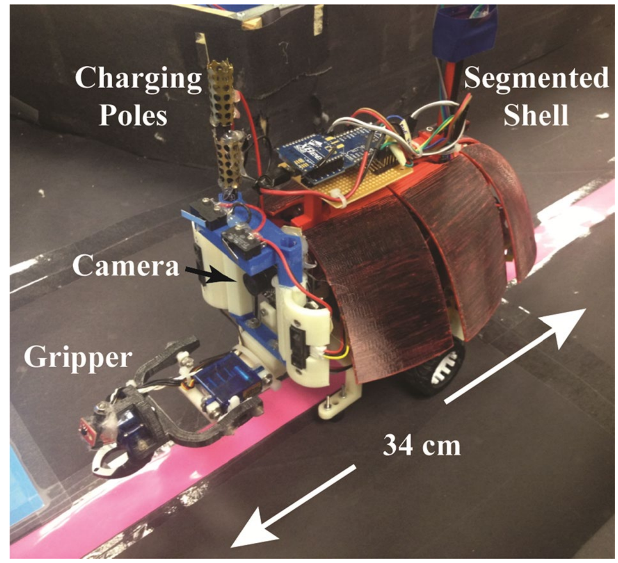

Fig. 2 Robotic excavator with important components labeled

simulated model, and understanding of limitations of the simulated system. We constructed our experimental robots to be behaviorally flexible, robust and affordable. Each robot used a low cost camera system (Pixy CMUcam5), as well as a gyroscope, and a magnetometer (relying on magnetic field of the Earth) to navigate. Two infrared distance sensors were used to detect and avoid objects directly ahead. Robot forward movement and turning were generated by a wheeled differential drive system. Excavation was performed with a small claw style gripper actuated with a servo motor.

The gripper was mounted on an arm, the pitch of which could be adjusted with another servo motor. An infrared proximity sensor was used to detect successful collection of the media. The robot detected interactions with the other robots and the tunnel using mechanical switches embedded beneath a segmented robotic shell: each shell segment rested on a mechanical switch which was triggered by physical contacts within the environment. Thus, not only the contact, but also its approximate direction was sensed. The robot was able to log its power consumption and instantaneous operation mode (locomotion, excavation, charging, soil deposition, etc.) to a micro SD card.

The robot could autonomously locate the charging bay and recharge when its battery voltage was low. Three robots were built, one of which is shown in Fig. 2.

2.3 Programmed behavior

An Arduino Due microcontroller was used to control behavior. Robots were programmed to follow a simple set of rules so that the behavior could be triggered by the local state of the surrounding environment. Each robot was programmed to search for the media using visual clues and onboard sensors. The pheromone trail was used as a visual cue to guide robot motion along the tunnel. The robot attempted to drive around obstacles (or other robots) detected with IR distance sensors. Once the excavation site was found, the robot collected a clump of media. After successful collection, the robot turned around and drove to the end of the tunnel. The robot then deposited its excavated payload into the collection bin. When the robot sensed a physical contact with its segmented shell, it would attempt to steer in a direction away from the contact, as well as to drive backwards in order to resolve a potential clog.

The robots operated completely autonomously without a centralized controller or sophisticated motion planning. Each robot performed actions in response to what it perceived in the environment without communicating with other robots.

2.4 Experimental protocol

To reveal the effects of confinement on the performance of the diggers, we varied the tunnel width. Groups of one, two, and three robots ($n = 1$, 2 and 3) were challenged to excavate in the wide and narrow tunnels. The width of the narrow tunnel was twice the width of the single robot body (2 BW), while the width of the wide tunnel was three times the width of the robot body (3 BW). In natural and laboratory conditions in a diversity of soils, fire ants dig tunnels approximately 2 body lengths wide [8]. The combined number of deposits (N) performed by the robots in the system was used to measure the excavation progress. In prior experiments, all robots were tested individually and displayed similar individual energy consumption over time (analogous to metabolic costs in animals). The combined energy consumption E was used to measure the performance of the system. The objective of the experiments was to explore how the average excavation rate ($\mathrm{d}N/\mathrm{d}t$) of the robotic group and the combined energy consumption ($\mathrm{d}E/\mathrm{d}N$) per group deposit per robot depended on the conditions of the experiment (BW, n).

2.5 Simulation

The construction and operation of the robots were time consuming. Therefore, to understand how the space confinement affected dynamics of the excavation by groups of diggers larger than experimental group, we developed a 2D cellular automata (CA) model similar to the one reported by Gravish et al. [11]. A schematic of a CA model is shown in Fig. 3. The model incorporated our hypothesized rules of the excavation organization in confined spaces. The lattice sites of the model were occupied by robots, tunnel or soil. A single lattice site was equal in size to the robot body length. The time of each simulation step was equal to 2 s of the experimental time. At the beginning of the simulation, the tunnel was set to be 7 robot body lengths long and 2 or 3 BW wide, in order to match the length of the test bed from the deformable media to the deposit bin in the experiment (Fig. 1). The unloaded robots moved towards the excavation site. At each iteration step, a robot advanced one step forward unless the lattice site was occupied by another robot. In this case, the robot moved to the site adjacent to the occupied site with probability p. This probability defined the duration of the "clog" and was chosen to match the duration of clogs observed in the experiments. When the size of the group was $n > 3$, each robot was given a small probability to turn back and exit the tunnel without excavation. At the tunnel face, the robot paused, excavated a pellet and then changed its state to "loaded". The loaded robot turned back and transported the pellet towards the tunnel exit, where the pellet was removed from the tunnel and the process repeated. When a certain number of pellets was excavated, the tunnel increased in length.

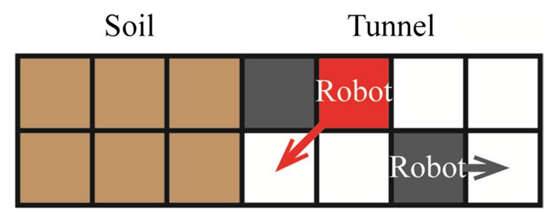

Fig. 3 Schematic of the cellular automata model for a 2 BW tunnel. The cells in the model are in one of the four states: soil (brown), tunnel (white), ascending ant (gray), descending ant (red). In experiment, width of the narrow tunnel is slightly larger than 2 BW and is equal to 41 cm (color figure online)

At every simulation step, the robots were characterized by their position (x, y), direction of motion, and energy. Each simulated robot was assigned the amount of energy equal to the battery charge of the robot in the experiment. The rate of the energy consumption of a single robot per unit time was constant, determined experimentally and converted to energy consumption per simulation step. The combined amount of energy spent by the group of robots in the simulations to deposit one pellet divided by the group size, as well as the number of deposits per unit time, was estimated and compared with the experimental data.

3 Results and discussion

In all experimental conditions, the robots were able to autonomously perform multiple excavations over several hours. The systems with multiple active robots revealed the emergence of interesting interaction behaviors. Because of

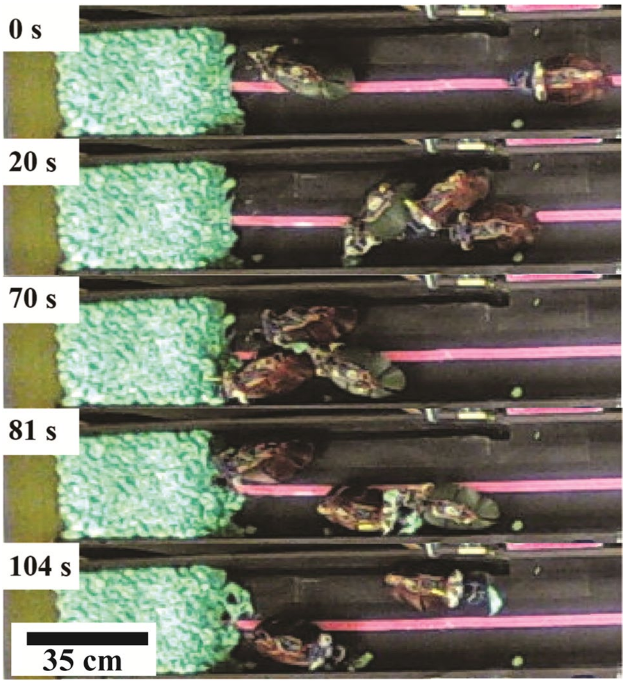

Fig. 4 Snapshots showing the clogging of three robots in the narrow tunnel (2 BW) near the excavation site

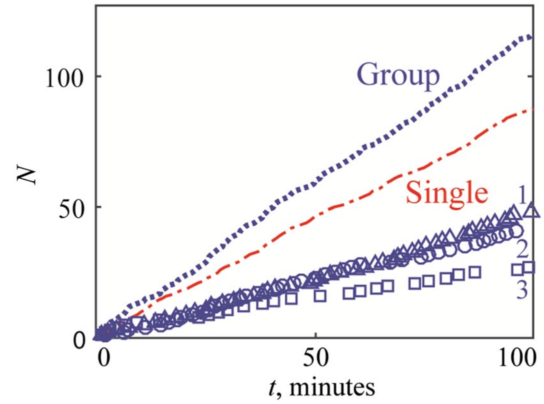

Fig. 5 Number of deposits performed in a wide tunnel experiment (3 BW) by a robot excavating alone (*dash-dot line*), by individual robots excavating in a group of three (*empty circles*, *triangles*, *squares*), and the net excavation effort of these three robots (*dotted line*) as a function of time

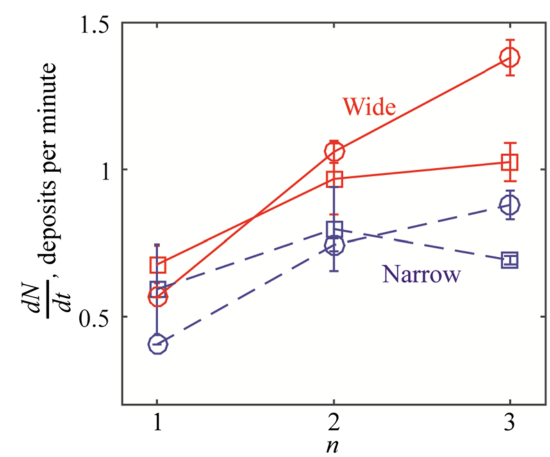

Fig. 6 Experimental (*square markers*) and simulated (*circular markers*) excavation rates (dN/dt) of systems with different number of robots (n) in both narrow (2 BW, *dashed line*) and wide (3 BW, *solid line*) tunnels. *Error bars* indicate standard deviations

the confined environment, the robots were often unable to pass each other without a collision or a physical interaction (Fig. 4). These interactions were resolved by the robots performing simple sets of maneuvers. A consequence of interactions (clogs) between the robots was an increase in the time required for the robots to excavate and deposit the simulated media. An example of this is illustrated in Fig. 4. The figure shows snapshots of three robots clogging near the excavation site in a narrow (2 BW) tunnel captured by an overhead webcam. In this example, robots spent approximately 104 s to resolve the clog. In comparison, in the absence of interactions the robots required approximately 14 s to travel between the excavation and deposit sites.

As the number of the robots in the system increased, we observed two competing phenomena. First, the number and the duration of the interactions increased. As a result, individual robots in multi-robot systems performed fewer excavations over time compared to the excavation performance of a robot digging alone (Fig. 5). Second, as shown in Fig. 5, although each robot in a group excavated noticeably less, the group of robots together outperformed a robot digging alone because the work load was shared. This benefit of a collective excavation is shown in Fig. 6.

However, the narrow tunnel led to more complicated excavation dynamics: the decrease in the tunnel width caused non-trivial interplay between the clogging effect and the benefit of collective excavation.

In addition to the amplified clogging effect described above, the robot turning behavior was also complicated by the space confinements. As a result of the confinement in the narrow tunnel, a reversal of the robot direction took additional time and effort. Thus, overall, a decrease in the tunnel width caused a decrease in the tunnel excavation rates (Fig. 6).

In the narrow tunnel, the benefits of collective excavation still outweighed the clogging effect. In this tunnel, both two and three robot systems on average excavated slightly faster or at least as fast as a single robot. However, the two-robot system had higher excavation rates than the three-robot system due to decreased clogging.

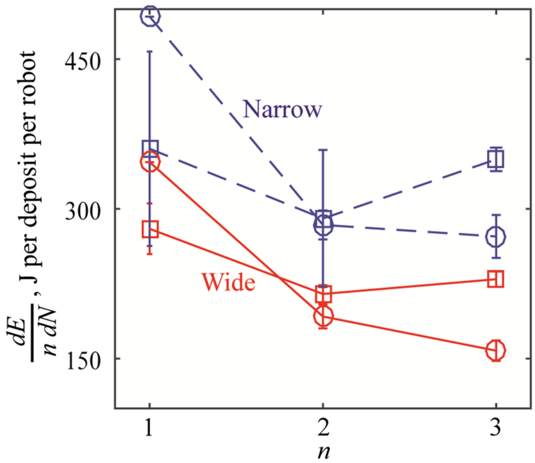

Fig. 7 Experimental (*square markers*) and simulated (*circular markers*) energy consumption per deposit per robot rates plotted versus the number of robots in the system for a wide (3 BW, *solid line*) and narrow (2 BW, *dashed line*) tunnels. *Error bars* indicate standard deviations

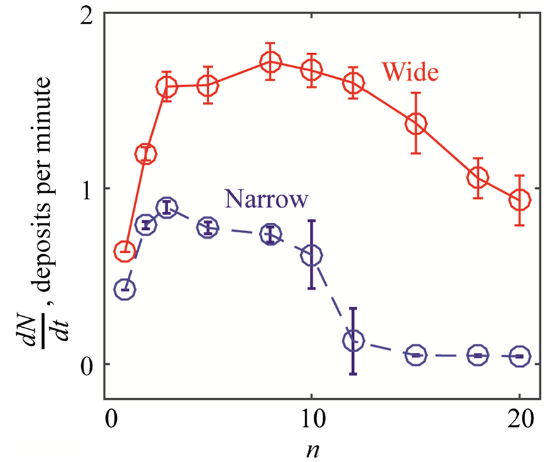

Fig. 8 The dependence of excavation rate (*dN/dt*) on the number of robots in the tunnel (*n*) acquired in the simulations in wide (solid line) and narrow tunnel (dashed line) tunnel. *Error bars* indicate standard deviations

Measurements of the energetic costs of excavation (1/*n*)·(d*E*/d*N*), are shown in Fig. 7.

The cellular automata model provided additional insight into phenomena revealed in the experiment. Due to geometrical constraints and the absence of physical effects (including surface friction, media cohesiveness, and individual robotic motion patterns and turning behaviors), the CA model underpredicted clogging. However, the results of the model showed trends similar to those observed in the experiments for both narrow and wide tunnels (Figs. 6, 7).

In both narrow and wide tunnels, the dependence of combined energy expenditure per robot per deposit (1/*n*)·(d*E*/d*N*) on the number of excavating robots was similar. Overall the energy cost of excavation in the narrow tunnel was higher than in the wide tunnel due to confinement. Also in wide and narrow tunnels, the robots digging in groups of two consumed the least amount of energy per excavation, since the workload was shared and the clogging was moderate. Although clogging took place in the wide tunnel in the three robot system, the combined energy consumption per robot per excavation was still lower in comparison to one robot system. In the narrow tunnel, the complexity of a turning behavior as well as additional clogging led to a high energy cost associated with each excavation trip (1/*n*)·(d*E*/d*N*). As a result, the groups of three robots in a narrow tunnel showed similar energetic costs as a robot digging alone.

As the tunnel width decreased, crowdedness increased, and this resulted in lower tunnel excavation rates and a larger energy cost of excavation per robot (Figs. 6, 7). The results of the CA model revealed that with a sufficient increase in the number of excavating robots the negative effect of clogging outweighed the benefit of collective excavation. In sufficiently large groups of independent diggers, solitary excavation becomes more efficient in terms of both excavation rates and energetic costs (Figs. 8, 9); for example, simulated groups of more than ten robots dug more slowly than a solitary robot working in a narrow tunnel.

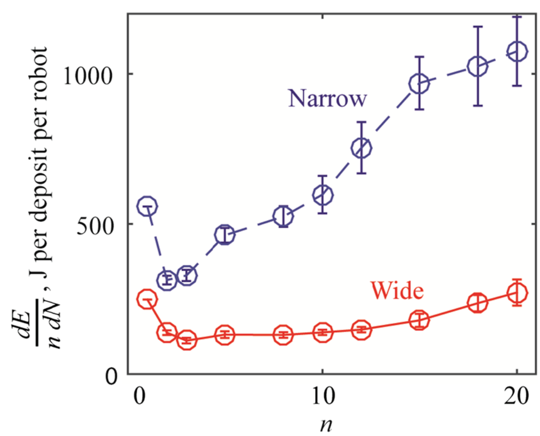

Fig. 9 The dependence of energy consumption per excavation per robot on the number of robots in the tunnel (*n*) acquired in the simulations in wide (*solid line*) and narrow tunnels (*dashed line*). *Error bars* indicate standard deviations

We expect that this transition is determined by traffic conditions in the tunnel. At some group size, the traffic becomes dense and robots spend time resolving traffic jams and performing complex unjamming maneuvers instead of actively excavating. We expect that this group size is influenced by friction and other physical interactions and would depend on the tunnel width.

4 Conclusion

Our robophysical experiment and simulations reveal how group performance during excavation is affected by spatial confinement. Even in small groups of robots working in narrow tunnels, the efficiency of the individuals was reduced due to clogging. We posit that efficient collective organization in confined spaces is a crucial requirement for successful excavation and expect that further research on biological swarms will inspire solutions for organization of multi-robot systems in confined spaces. We hypothesize that when the physical effects of clogging cannot be avoided, social insects can reduce clogging through social behaviors aimed at traffic regulation that include social workload heterogeneity, pheromone signaling, information exchange through antennal contacts, and development of complex networks with multiple interconnected tunnels. The combined experiment/simulation framework we have developed will be used to further study the physical (and social) principles of collective excavation.

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References

1. Wilson EO (1990) Success and dominance in ecosystems: the case of social insects. Ecology Institute, Federal Republic of Germany, Oldendorf/Luhe
2. Wilson EO (1971) The insect societies. Harvard University Press, Cambridge
3. Turner JS (2000) The extended organism: the physiology of animal-built structures. Harvard University Press, Cambridge
4. Hölldobler B, Wilson EO, Nelson MC (2009) The superorganism : the beauty, elegance, and strangeness of insect societies. W.W. Norton, New York
5. Monaenkova D, Gravish N, Rodriguez G, Kutner R, Goodisman MAD, Goldman DI (2015) Behavioral and mechanical determinants of collective subsurface nest excavation. J Exp Biol 218:1295–1305. doi:10.1242/jeb.113795
6. Theraulaz G, Bonabeau E (1999) A brief history of stigmergy. Artif life 5(2):97–116. doi:10.1162/106454699568700
7. Keller L, Chapuisat M (1999) Cooperation among selfish individuals in insect societies. Bioscience 49(11):899–909. doi:10.2307/1313649
8. Gravish N, Monaenkova D, Goodisman MAD, Goldman DI (2013) Climbing, falling, and clogging during ant locomotion in confined environments. Proc Natl Acad Sciences USA 110(24):9746–9751. doi:10.1073/pnas.1302428110
9. Tschinkel WR (2006) The fire ants. Belknap Press of Harvard University Press, Cambridge
10. Cao TT, Dornhaus A (2008) Ants under crowded conditions consume more energy. Biol Lett 4(6):613–615. doi:10.1098/rsbl.2008.0381
11. Gravish N, Gold G, Zangwill A, Goodisman MA, Goldman DI (2015) Glass-like dynamics in confined and congested ant traffic. Soft Matter 11(33):6552–6561. doi:10.1039/c5sm00693g
12. Aguilar J, Zhang T, Qian F, Kingsbury M, Benjamin M, Mazouchova N, Li C, Maladen R, Gong C, Travers M, Hatton RL, Choset H, Umbanhowar PB, Goldman DI (2016) A review on locomotion robophysics: the study of movement at the intersection of robotics, soft matter and dynamical systems. Reports on Progress in Physics **(in press)**