Robophysical Study of Excavation in the Confined Environments

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Abstract: Nest excavation in social insects is an integral part of a colony's life cycle. Soil-dwelling colonies build complex systems of narrow underground chambers and tunnels spanning thousands of insect body lengths below the ground. The nest excavation is performed by multiple animals simultaneously and is governed by local interactions of the workers with environment and other workers. The challenges and advantages of such a system are poorly investigated, mainly due to the complexity of the biological system and the lack of experimental control on animal behavior. To address this problem we designed and built groups of robotic excavators, capable of performing days of autonomous tunnel excavation in a model cohesive granular media. The excavator behavior was governed by a simple set of rules triggered by interactions with the surrounding environment. In the experiments we tested the effect of the tunnel width and the size of the excavating group on the rate of the tunnel growth and the energetic costs of excavation for individual workers. An experimentally validated cellular automata model was developed to extend experimental results to systems with larger numbers of robots. The experimental data and simulations showed that in sufficiently wide tunnels the increase in the size of the excavating group had a positive effect on the tunnel excavation rates without significant increase in the energy consumption per robot. A decrease in the tunnel width resulted in a decrease in the tunnel excavation rates and increase in the energetic costs of excavation per robot. We attribute this effect to the emergence of multiple interactions (jams) among excavating robots in the confined spaces. Although the jams were successfully resolved based on local mechanical interactions of the robots in the tunnel, their presence slowed the excavation down appreciably. The duration of jams was longer in the systems with higher number of robots or narrower tunnels. We expect that despite its relative simplicity our robotic system can be used to investigate the behavior of social insects in the confined spaces as well as inspire more sophisticated robotic search-and-rescue teams in crowded environments.

Keywords: Robots, ants, social insects.

1. INTRODUCTION

The ecological success of the social insects is overwhelming [1]. These animals live in large societies often encountering more than a million of individuals [2]. The nests of the 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 the space to perform social functions, including mating, brood care, communication, food sharing, provision and defense [3,4]. The nest excavation proceeds through the excavation of soil agglomerates by multiple workers simultaneously [5]. The excavation occurs through the simple low-level interactions of the excavators with environment in the absence of a centralized control [6]. The outcome of the collective excavation thus is a composite of the efforts of the individual workers. We expect that the increase in the number of workers reduces the amount of work performed by a single animal and presumably the cost of nest excavation per animal, as well as it may increase the rates of the nest excavation. However, it is unclear if these predictions are valid for subterranean social insects, whose nests consist of interconnected tunnels and chambers [7].

Social insects, like fire ants, build their nests in conditions of rough terrain, deprived vision, high locomotion speeds, confined environment and crowdedness [8]. The latter becomes especially important, when the number of animals working in the narrow tunnel increases. Although some experimental work has been done on the costs and benefits of subterranean nest excavations [9], the advantages of collective excavations in such conditions are yet to be understood.

We hypothesized that an important challenge in confined spaces is the establishment of steady traffic flow conditions. We expect that social insects approach this problem through the set of complex excavation organization behaviors. However, following [10] we posit that the role of jamming and glass-like states of flow cannot be ignored. In this paper we reveal physical principles behind the collective excavation in confined spaces through robotic and experimentally validated simulated diggers capable of continuous collective autonomous excavation. The effect of the group size on the costs and benefits of excavation is non-trivial and largely depends on the size of the tunnel. The results of the models demonstrate the importance of jam mitigation strategies during confined behaviors.

2. EXPERIMENTAL SETUP

2.1 Test bed design

A small group of autonomous robots was designed to operate within a simulated artificial environment. The environment consisted of a table top testbed (Figure 1), featuring a quasi 2D tunnel, a charging bay and a media deposit area. The tunnel was partially filled with a cohesive deformable simulated media (colored cotton balls). The width of the tunnel could be adjusted by changing the distance between the wooden walls according to the experimental requirements. The visual guide (fluorescent tape) was secured to the tunnel floor in order to assist robots with navigation between the cohesive media and the deposit area. The charging station was also marked with a unique visual clue.

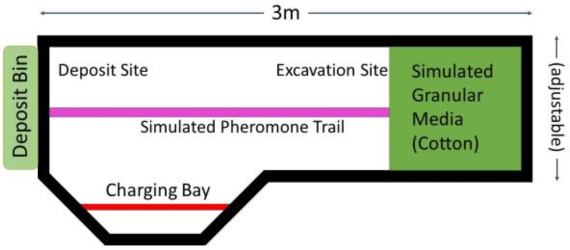

Fig.1 Schematic of a table top test bed with adjustable tunnel walls.

2.2 Robot design

Each robot used a low cost camera system (Pixy CMUcam5), as well as a gyroscope, and a magnetometer to navigate. Two infrared distance sensors were used for detecting and avoiding objects directly ahead. Robot locomotion was enabled by a differential wheeled drive system. Excavation was performed with a small claw style gripper actuated with a servo motor.

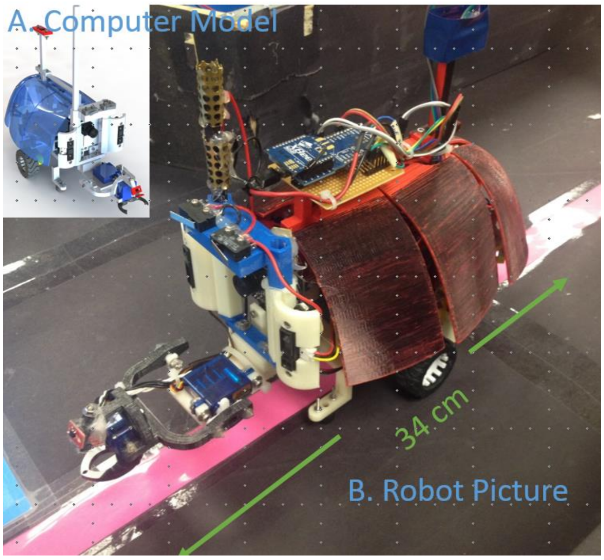

Fig.2. A computer model (A) insert in the main figure. The main figure shows a picture of the robot (B). The robot is 17 cm wide, 34 cm long, and 25 cm tall.

The gripper was mounted on the arm, the pitch of which could be adjusted with another servo motor. An infrared proximity sensor was used to detect successful collection of the model media. The robot could detect interactions with the other robots and the tunnel with 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 record and store the power consumption and the current operation mode (locomotion, excavation, charging, soil deposition, etc.) to a micro SD card. The robot could autonomously find the charging bay and recharge itself when it detected that it was low on energy. Three robots were built. A design of a robot is shown in Figure 2.

2.3 Programmed behavior

The robot featured the Arduino Due microcontroller carrying the software 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 simulated cohesive media by using visual clues and onboard sensors. The robot would attempt to drive around obstacles (or other robots) which would be detected with IR distance sensors. Once the excavation site was found, the robot attempted to collect a soil clump. After successful collection, the robot turned around and drove to the end of the tunnel. Once at the end, the robot would deposit its excavated payload into the collection bin. When the robot sensed a physical contact with its segmented shell, the robot would attempt to steer in the direction away from the contact, as well as to drive backwards in order to resolve the jam.

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

In order to reveal the effect of space 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 set to excavate in the wide and narrow tunnels. The width of the narrow tunnel was twice the width of the single robot body frame (2 BW) while the width of the wide tunnel was three times the width of the robot body frame (3 BW). In nature ants dig tunnels approximately 2BL wide. The total number of deposits (N) performed by the robots in the system was used to measure the excavation progress. In prior experiments, all robots were individually tested and found to have a similar energy consumption over time (analogous to metabolic costs in animals). Thus, it was decided to introduce the average energy consumption per robot as a total energy (E) expense of the system normalized by the number of robots participating in the experiment. The objective of the experiments was to explore how the excavation rate (dN/dt) and the energy consumption per deposit (dE/dN) per robot depend on the conditions of the experiment (BW, n).

2.5 Simulation

To understand how the space confinement affected dynamics of the excavation by groups of diggers we developed a 2D cellular automata (CA) model. The model reflected our hypothesized basic rules of the excavation organization in confined spaces. The lattice sites of the model were occupied by robots, tunnel or soil. The unloaded robots moved towards the excavation site. Each iteration 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 "jam" and was chosen to match the duration of jams observed in the experiments. When the size of the group was n>3, each robot had 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 certain number of pellets was excavated the tunnel increased in length. At every simulation step the robots were characterized by their position *(x,y)*, direction of motion and energy. Similar to the experimental system, energy was introduced to measure the energy expenditure within the excavating group upon tunnel excavation. Schematic of a CA model is shown in Figure 3.

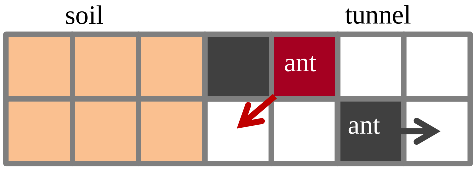

Fig. 3. Schematic of cellular automata model for 2 BW tunnel. The cells are in one of four states: soil, tunnel, ascending ant, descending ant.

3. DISCUSSION

In all experimental conditions the robots were able to autonomously perform multiple excavations over extended periods of time. The systems with multiple active robots revealed the emergence of interesting interaction behaviors. Because of the confined environment, the robots were often unable to pass each other without a collision or a physical interaction (Figure 4). These interactions where resolved by the robots performing simple sets of maneuvers. The consequence of interactions (jams) between the robots was an increase in the time required for the robots to excavate and deposit the simulated media. The example of this is illustrated in Figure 4. The figure shows snapshots of three robots jamming near the excavation site in a narrow (2 BW) tunnel captured by an overhead webcam. In the example shown in Figure 4, robots spent approximately 104 seconds to resolve the jam. In comparison, in the absence of interactions the robots required approximately 14 seconds to travel between the excavation and deposit sites.

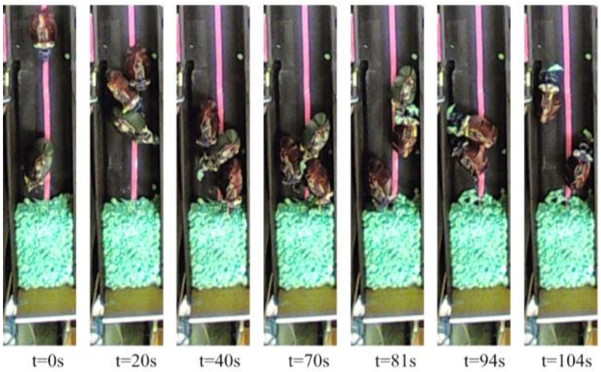

Fig.4. Snapshots showing the jamming of three robots in the narrow tunnel (2 BW) near the excavation site.

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 with the number of the excavating robots. As a result, individual robots in multi robot systems were performing fewer excavations over time compared to the excavation performance of a robot digging alone. (Figure 5). Secondly, as shown in Figure 5, even though each robot in a group excavated noticeably less, the group of the robots together outperformed a robot digging alone because the work load was shared. This was a benefit of a collective excavation.

According to the experimental data obtained in the wide tunnels, the increase in the number of robotic diggers increased the excavation performances of the group (Figure 6). However, this was not true in the narrow tunnel. The decrease in the tunnel's width caused non-trivial interplay between the jamming effect and the benefit of collective excavation.

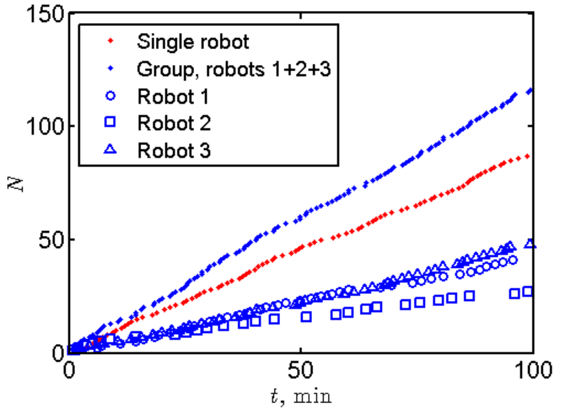

Fig. 5. Number of deposits performed in a wide tunnel (3 BW) by a robot excavating alone (red dots), by individual robots excavating in a group of three (blue squares, triangles, and circles), and the summarized excavation effort of these three robots (blue dots) as a function of time.

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

In the narrow tunnel the benefits of collective excavation still outweighed the jamming effect. In the narrow tunnel, both two and three robot systems on average excavated slightly faster than a single robot. However, the two robot systems had higher excavation rates than a three robot system due to less jamming.

The measurements of the individual energetic costs of excavation *(1/n)·(dE/dN)*, i.e. average energy consumed by individual robots in a group per excavation instance, are shown on the Figure 7.

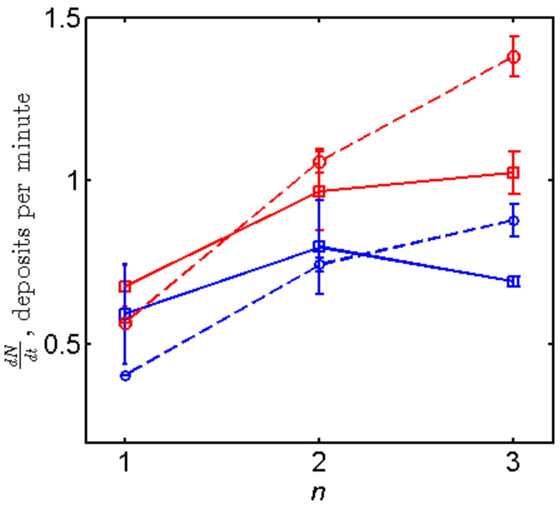

Fig. 6. Experimental (solid lines with square markers) and simulated (dashed lines with circular markers) excavation rates (*dN/dt*) of systems with different number of robots (*n*) in both narrow (2 BW, blue) and wide (3 BW, red) tunnels.

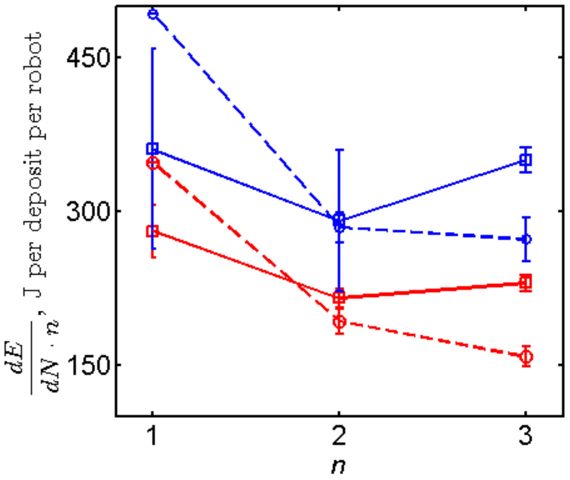

Fig. 7. Experimental (solid lines with square markers) and simulated (dashed lines with circular markers) energy consumption per deposit per robot rates plotted versus the number of robots in the system for a wide (3 BW, red) and narrow (2BW, blue) tunnels.

In both narrow and wide tunnels the general dependence of energy expenditure per robot per deposit *(1/n)·(dE/dN)* 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 jamming was moderate. In the wide tunnel the three robot systems were still less energy expensive than the one robot system, despite increased jamming. In the narrow tunnel, the complexity of turning behavior as well as additional jamming translated into a high energy cost associated with each excavation trip *(1/n)·(dE/dN)*. As a result, the groups of three robots in a narrow tunnel showed similar energetic costs as a robot digging alone.

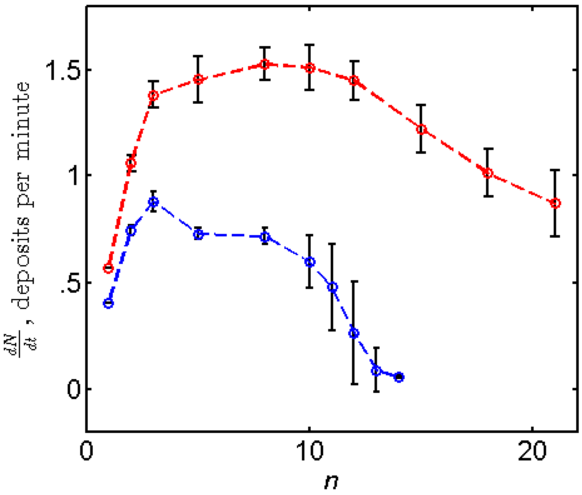

Fig. 8. The dependence of excavation rate (*dN/dt*) on the number of robots in the tunnel (*n*) acquired in the simulations in wide (red circles) and narrow tunnel (blue circles) tunnel.

Although, the cellular automata model underpredicted jamming for three robots system, the results of the model show trends similar to those observed in the experiments for both narrow and wide tunnels (Figure 6, 7). As the crowdedness increases the tunnel excavation rate begins to decrease and the energy cost of excavation per robot grew (Figure 8, 9).

When the number of robots exceeded a critical value, the solitary excavation became more efficient in terms of both excavation rates and energetic costs (Figure 8, 9). In the wide tunnel this critical value is larger than in the narrow tunnel. Thus the density of the robots in the tunnel is one of the most important parameters defining efficiency of construction.

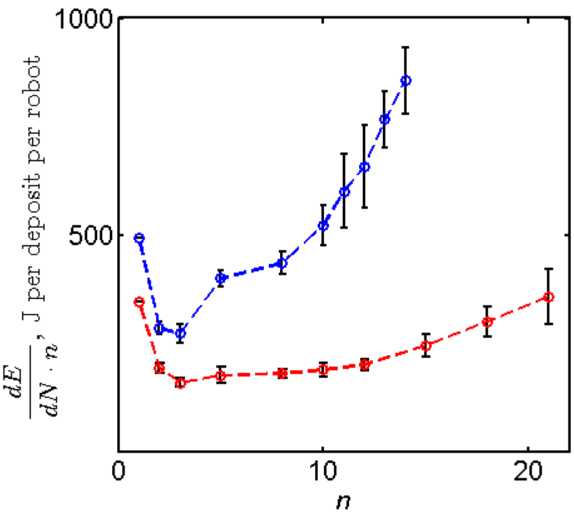

Fig. 9. The dependence of energy consumption per excavation per robot on the number of robots in the tunnel (*n*) acquired in the simulations in wide (red circles) and narrow tunnel (blue circles) tunnel.

Regarding comparison of experiment and simulation, due to geometrical constrains and the absence of physical effects, including surface friction, media cohesiveness, individual robotic motion patterns CA model underpredicted jamming. Even though the jamming in the model was reduced, the results of the CA modeling showed that with a sufficient increase in the number of excavating robots the effect of jamming outweighs positive effect of collective excavation and in sufficiently large groups of independent diggers solitary excavation becomes more efficient. In the simulations the groups of more than ten robots dug slower than a solitary robot. We expect that in the tested robotic system this critical group size will be even lower. We hypothesize that the social insects avoid this problem through more complex excavation organization behaviors, possibly including pheromone signaling, information exchange through antennal contacts, development of complex networks with multiple interconnected tunnels. However, the physical and social aspects of jamming cannot be completely avoided.

4. CONCLUSION

Our models reveal the importance of spatial confinement on group performance during excavation. Even in small groups of robots working in narrow tunnels the efficiency of the individuals was reduced due to jamming. 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. The combined experiment/simulation framework we have developed will be used to further study the physical (and social) principles of collective excavation. In the future we plan to enrich the model and robotic system with social organization principles found in large biological swarms.

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