

# Controlling Ant-Based Construction

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**Abstract:** *Stigmergy allows insect colonies to collectively build structures that no single individual is fully aware of. Since relatively minimal sensory and reasoning capabilities are required of the agents, such building activity could be utilised by robotic swarms if we could learn how to control the shape of the final structures. This paper investigates dynamics of ant nest building and shows that algorithms capable of generating ant-like structures can also be used to create nests, shapes of which are imposed from outside of the system.*

**Keywords:** construction, ants, robots

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## 1. Introduction

Insect-inspired behaviours like sorting, foraging and building that involve self-organisation and emergence are fascinating phenomena to study. While individuals only rely on local probabilistic interactions with the world (Theraulaz et al., 1998), colonies can deal with dynamic, large-scale problems (Di Marzo Serugendo et al., 2011). They achieve this through positive feedback involving work recruitment and reinforcement, counterbalanced by physical restrictions that represent negative feedback, while novelty is assured by amplification of random fluctuations (Bonabeau et al., 1997).

When building their nests, insect colonies are capable of creating extremely complex structures, explicit blueprints of which do not exist in the simple individuals (Theraulaz et al., 1998). Such collective building is possible through stigmergy, where deposition of building material, and in case of termites pheromone as well, attracts other nest mates to build there. For example, some ant species progressively encircle their brood with a wall (Franks et al., 1992), whereas paper wasps build combs organised to larger pedicles that are sometimes protected by

an external envelope (Jeanne and Bouwma, 2002; Pilat, 2004). Termites are capable of building highly complex nests with ventilation shafts, galleries, brood chambers, fungus gardens and royal chambers (Bonabeau et al., 1998).

Due to its parallel nature, insect nest building is prone to opposing actions and needless redundancies are created (Di Marzo Serugendo et al., 2011). Nevertheless, the fact that the individuals themselves only require limited sensors, memory and reasoning (Mason, 2002) makes attempting to reproduce them as robots attractive (Holland and Melhuish, 1999; Parker and Zhang, 2006). In the future, we might be able to rely on extremely simple and cheap robots to use environmental cues supplied by us in order to build structures around them. For example, we could place signal beacons to suggest where corners of a building should be or where space should be created for windows and doors.

In order to be able to control insect-like construction, we must first understand it. This paper investigates nest building by the ant *Leptothorax tuberointerruptus* that creates circular structures with one or more entrances around its brood. The nests are created inside flat horizontal cavities and can thus be studied in two dimensions (Franks

et al., 1992; Franks and Deneubourg, 1997; Theraulaz et al., 2003). Ant builders divide into ‘internal’ and ‘external’. Internal ants stay in a close proximity to the brood cluster and tend to push stones away from it, while external ants search for stones in the environment. After finding new stones, they push them directly towards the cluster until they collide with another ant or a wall, at which point they turn by 180 degrees and actively bulldoze stones into other stones.

The brood cluster and the internal ants serve as a physical template for construction, especially at the beginning of the process. As they become encircled with stones, the structure itself becomes more important for stigmergy and new stones are often bulldozed into walls from outside of the nest. Building can occur at several places at once, in which case stones might travel between building sites as different ants pick them up and drop them.

There is a certain ambiguity in the literature about the role of pheromone that emanates from the brood cluster. It is clear that ants use it to orient themselves within the nest (Franks et al., 1992), but it is not yet empirically established whether pheromone influences stone deposition (Franks and Deneubourg, 1997). Furthermore, while global colony behaviour is well described (Franks et al., 1992) and modelled analytically (Franks and Deneubourg, 1997), existing agent-based simulations are either in grid worlds where noisy movement and bulldozing with friction are not modelled (e.g. Franks et al., 1992) or use simple continuous behaviour where ants are only of one type (e.g. Theraulaz et al., 2003). Moreover, Theraulaz et al. assume that ants are able to perceive stone density around them, even though real ants are blind, and that they use this density as well pheromone concentration to drop stones.

This paper attempts to achieve a better understanding of how the radius and integrity of the nest result from the local interactions of ants in a continuous world model, where the inaccuracies of the previous models are addressed. In particular, the following hypotheses are tested:

1. Nests will be larger when there will be more internal ants in the colony and smaller when there will be more external ants.
2. Using the pheromone cloud as a template for building will create more regular structures, but will also interfere with the effect of the number of ants on the nest size.

3. Nest entrances will form when ant movement is less random and the pheromone template will further facilitate the creation.

Finally, transferability of this building behaviour into human-controlled robotic settings is explored:

4. By selecting appropriate ant behavioural parameters, it will be possible to arrange a number of pheromone clouds in order to create rectangular and triangular nests.

## 2. Methods

### 2.1. World

All simulations were performed in a two-dimensional continuous-space arena  $660 \times 660$  pixels large. One time step of the simulation update loop was executed each  $1/50$  seconds and each simulation run lasted 6000 seconds. World objects were scaled proportionally to real world objects as described by Franks and Deneubourg (1997), so that 1px represented 0.25mm. 3000 rectangular stones of size  $2 \times 2$  pixels (0.5mm in diameter) were placed randomly within the arena at the beginning of each run.

The brood was represented by a tight cluster of randomly oriented stationary ant agents placed around the middle of the arena in a random Gaussian fashion. A circular pheromone cloud of 300px in diameter was centred on the cluster so that the pheromone concentration had a constant value of 1 in the middle, linearly decreased and was 0 at the edges of the cloud.

### 2.2. Ants

The following paragraphs briefly describe some details of the implemented behaviour. A full algorithmic representation is given in Figures 1 - 3.

A number of ‘internal’ and ‘external’ rectangular ants  $10 \times 2$ px (2.5x0.5mm) large were initially placed around the brood cluster. Ant movement was simulated as continuous (Bourg and Seemann, 2004, p. 16-19), where the centre of an ant’s body was moved by a real-valued distance from range  $[0, 2]$  per time step, depending on its current speed and rotation.

Both ant types relied on the ability to sense the current pheromone concentration  $C_p$  and on remembering the highest pheromone concentration  $C_{p*}$  they had encountered so far, as well as where they

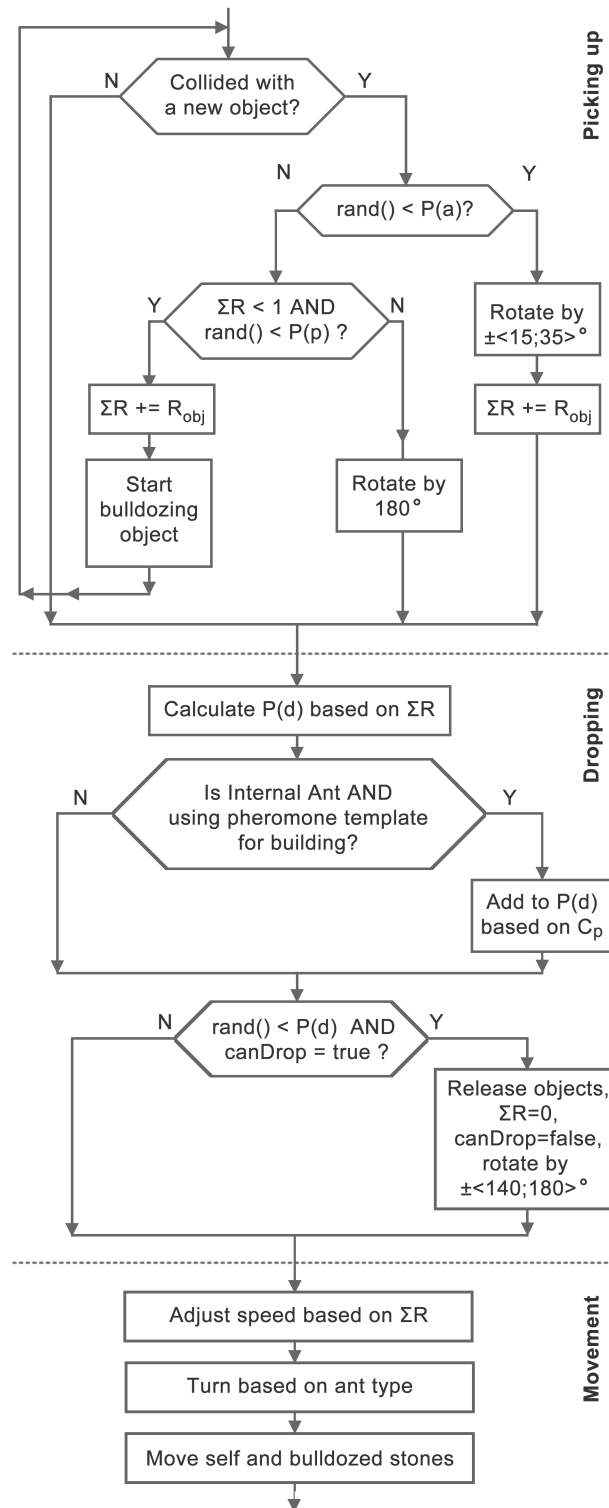


Figure 1: Ant's update loop

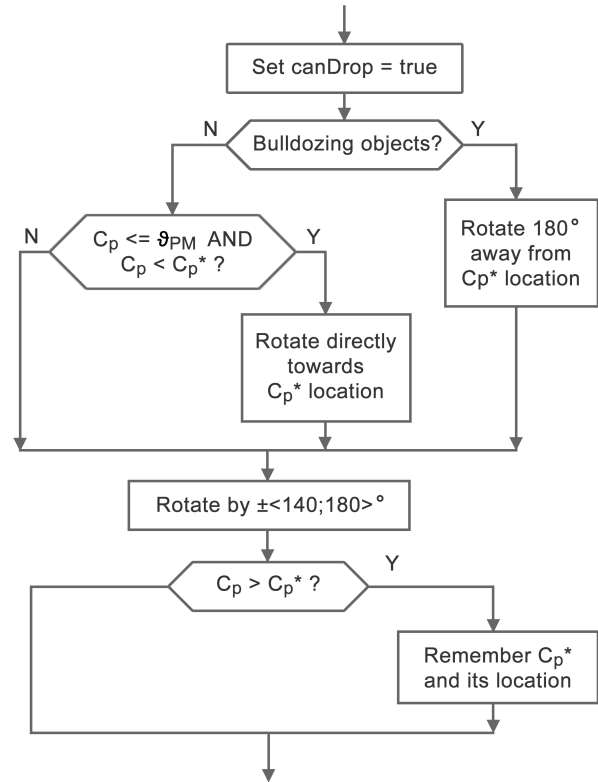
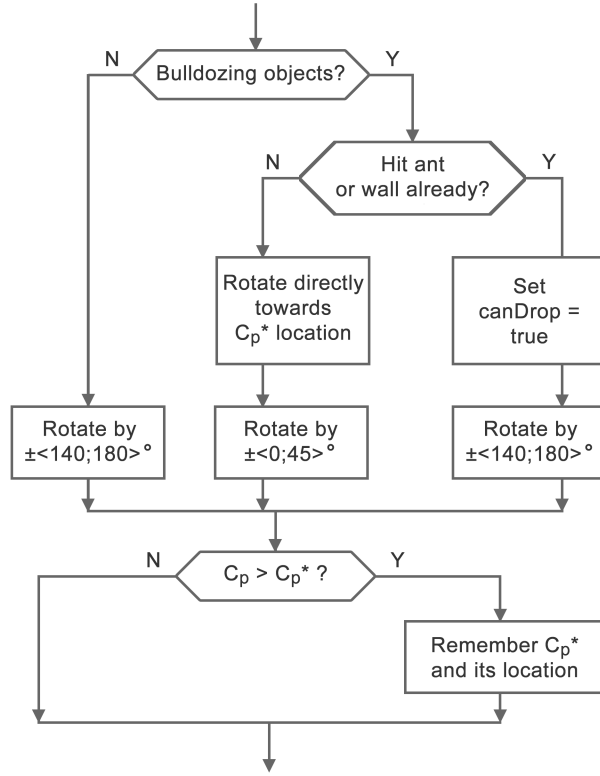


Figure 2: Internal ant's 'Turn based on ant type' routine

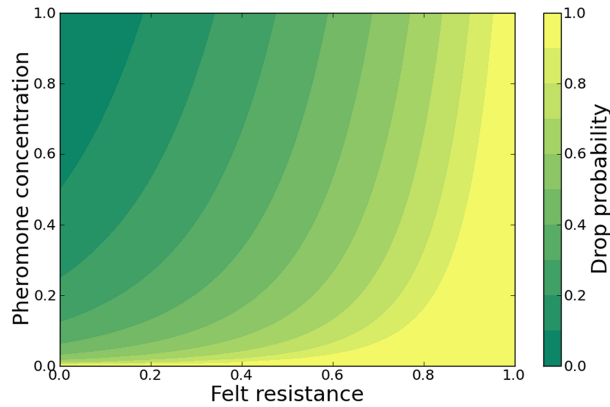
encountered it. The behaviour of internal ants (Figure 2) governed by pheromone movement threshold  $\vartheta_{PM}$  assured that they remained inside of the pheromone cloud when they were not bulldozing. The ants bulldozed stones towards the cloud edges and returned back when they dropped stones. On the other hand, external ants (Figure 3) moved randomly unless they were carrying stones towards the pheromone cloud. To comply with real ant behaviour, an external ant could only drop stones after it encountered an obstacle and turned away from it. Furthermore, randomness was added to movement of both ant types in order to match behaviour of real ants more closely.

Additionally, the ants implemented the following empirically observed behaviours (Franks et al., 1992):

1. Stone bulldozing, i.e. pushing of a single or multiple stones in front of them
2. Stone dropping, the probability of which increased with felt resistance



**Figure 3:** External ant's 'Turn based on ant type' routine



**Figure 4:** Contour plot of drop probability  $P(d)_i$  based on Equations 3 and 4. Values of  $P(d)$  only dependant on Equation 3 can be seen along the x axis for  $y=1.0$ , i.e. when the effect log of pheromone concentration is 0.

3. Stone dropping upon contact with a thick wall or another ant
4. Occasional moving along walls while bulldoz-

ing. In this case, an ant rotated by a small value as it approached an existing wall and continued its movement along it.

The probability of picking up stones when encountered was a constant  $P(p) = 0.5$ . Each pushed stone or stone that an ant was currently colliding with added resistance  $R_s = 0.15$  to the ant's total felt resistance  $\Sigma R \in [0, 1]$ . The resistance experienced during collisions with other ants was  $R_a = 1.0$ .

$\Sigma R$  affected the ant's speed  $s$  in relation to its maximum speed  $S_{max}$  (Equation 1), its probability of moving along walls  $P(a)$  (Equation 2) and the probability of dropping all pushed stones  $P(d)$  (Equation 3). Generally speaking, an ant pushing more stones moved slower, was more likely to move along walls and thus extend them rather than make them thicker and bulldozed stones for a shorter amount of time. Similarly, if a thick wall or another ant was encountered by an ant pushing only one stone,  $\Sigma R$  rapidly increased, the stone was dropped almost immediately and the ant turned away.

$$s = S_{max}(1 - \Sigma R); \quad S_{max} = 2 \quad (1)$$

$$P(a) = \Sigma R \quad (2)$$

$$P(d) = f \times |\log(1 - \alpha \times (\Sigma R + \epsilon))|; \quad (3)$$

$$f = 0.625, \alpha = 0.8, \epsilon = 10^{-11}$$

In experiments where the pheromone cloud was used as a template for building (template experiments), a value based on the current perceived pheromone concentration  $C_p$  was added to an internal ant's drop probability  $P(d)_i$  (Equation 4) so that it exponentially increased as the ant was moving towards edges of the pheromone cloud. The effect of both  $\Sigma R$  and  $C_p$  on  $P(d)$  is depicted on Figure 4.

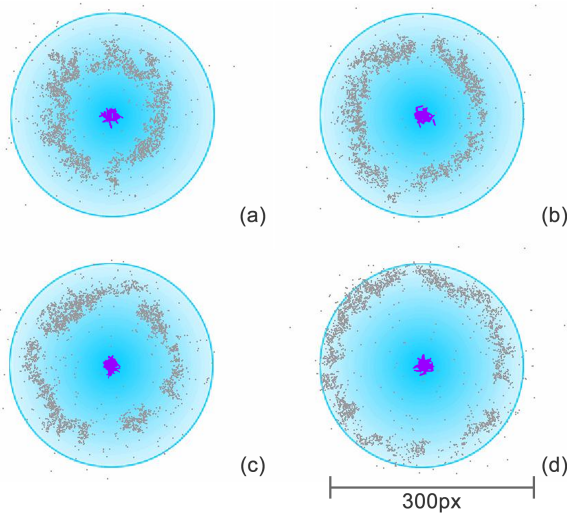
$$P(d)_i = \min(1, P(d) + |g \times \log(C_p)|); \quad (4)$$

$$g = 1/7$$

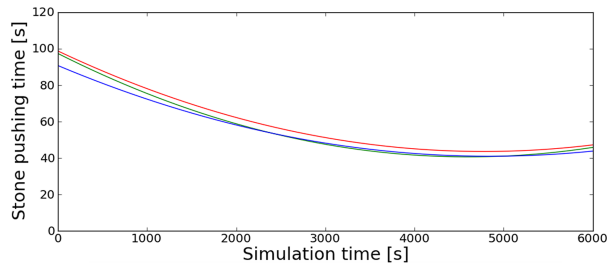
### 3. Nest formation results

#### 3.1. Comparison with previous models

All results presented in this paper are based on 20 runs each. Structures built by the artificial ants



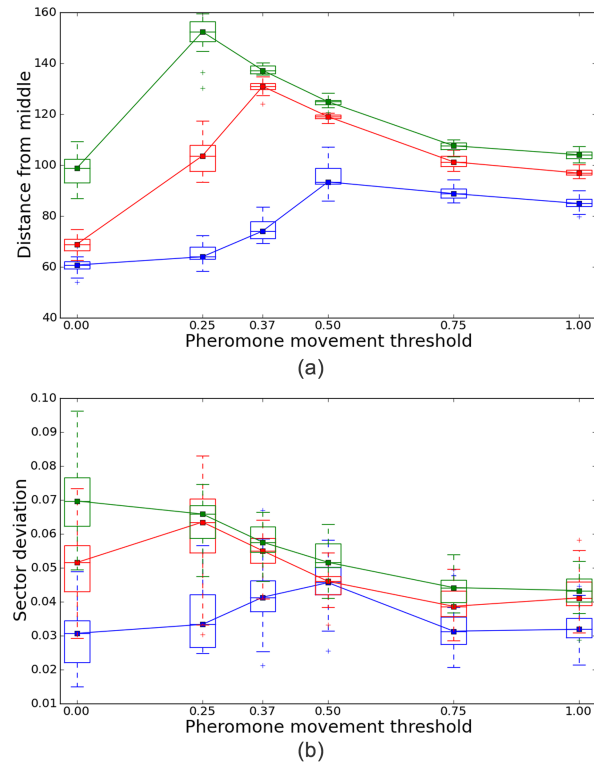
**Figure 5:** Example nests for various ant parameter combinations: a)  $N_i=10$ ,  $\vartheta_{PM}=1.0$ , b)  $N_i=30$ ,  $\vartheta_{PM}=0.75$ , c)  $N_i=50$ ,  $\vartheta_{PM}=1.0$ , d)  $N_i=50$ ,  $\vartheta_{PM}=0.5$ . The pheromone cloud is shown as blue gradient. Brood clusters placed in the arena centres are shown in purple.



**Figure 6:** Fitted 2nd order polynomial model of stone carry time measured for external ants between the moment they entered the pheromone cloud and the moment they dropped stones.  $N_i=30$ ,  $N_e=10$  and  $\vartheta_{PM}=1.0$  (red),  $\vartheta_{PM}=0.75$  (green),  $\vartheta_{PM}=0.5$  (blue)

were generally circular (Figure 5), with walls forming around the brood cluster and internal walls. This result was robust with respect to the colony size and suitable values of the pheromone movement threshold  $\vartheta_{PM}$  and is comparable with the real and simulated ants in the existing literature (Franks et al., 1992; Theraulaz et al., 2003).

The stone pushing time of external ants measured from point when they entered the pheromone cloud decreased as the simulation progressed irrespective of values of  $\vartheta_{PM}$  (Figure 6) due to progressively higher frequency of encountering already



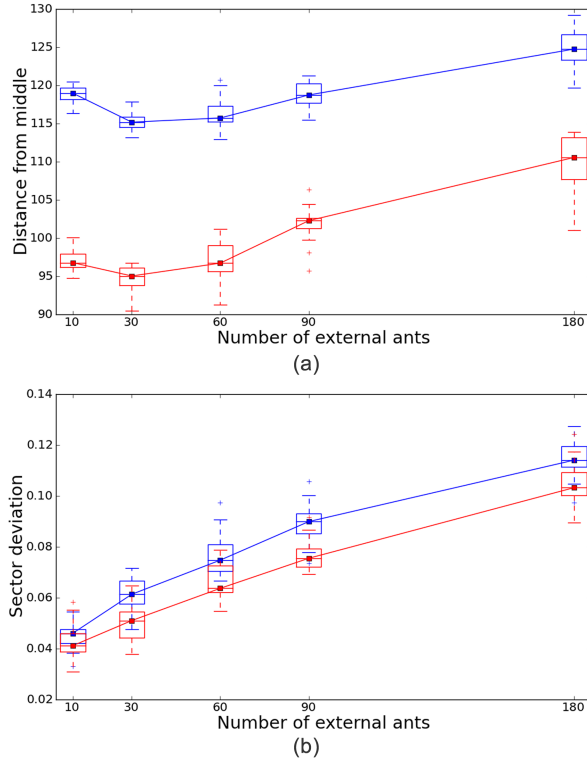
**Figure 7:** A) average distance of stones from the middle of the pheromone cloud and b) standard deviation of the number of stones in 8 conical sectors of the cloud using  $N_e=10$  and  $N_i=10$  (blue),  $N_i=30$  (red),  $N_i=50$  (green).

placed stones. This behaviour is comparable to the one described by Franks and Deneubourg (1997) who implied that stone carrying time decays exponentially as the nest building progresses.

### 3.2. Colony size

The size of nests built by real ant colonies depends on the number of colony members (Franks and Deneubourg, 1997). Similarly, a non-linear relationship between the diameter of final structures and the number of simulated internal ants  $N_i$  was found when  $N_e = 10$  (Figure 7a). The colony size also affected nest regularity measured as a standard deviation of the number of stones found in 8 conical sectors, each originating in the middle of the pheromone cloud (Figure 7b).

Nest regularity also depended on the values of  $\vartheta_{PM}$ , i.e. on how far from the brood cluster internal ants were ‘willing’ to roam before turning back towards it. Only when  $\vartheta_{PM}$  was higher than a specific

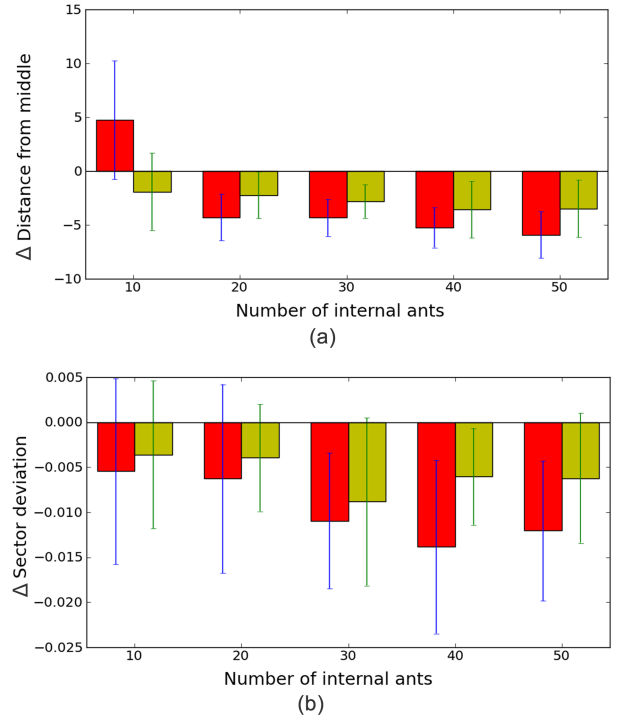


**Figure 8:** A) average distance of stones from the middle of the pheromone cloud and b) standard deviation of the number of stones in 8 conical sectors of the cloud using  $N_i=30$  and  $\vartheta_{PM}=0.5$  (blue),  $\vartheta_{PM}=1.0$  (red).

threshold  $\vartheta_{PM}^*$ , was a colony able to encircle itself with stones. The most regular structures appeared when  $\vartheta_{PM} = 1.0$ . Larger colonies were generally able to cope with smaller values of  $\vartheta_{PM}$  as they could fill larger spaces better ( $\vartheta_{PM}^* = 0.25$  for  $N_i = 50$ ,  $\vartheta_{PM}^* = 0.37$  for  $N_i = 30$  and  $\vartheta_{PM}^* = 0.5$  for  $N_i = 10$ ).

As  $\vartheta_{PM}$  approached 0, many stones were left very near the middle of the pheromone cloud, since external ants kept bringing them in but there was a low probability of a stone being approached by an internal ant. In these cases, the structures were very irregular and packed close to the brood.

When  $N_i$  was fixed to 30 and  $N_e$  increased from 10 to 30, the nests became smaller (Figure 8a) and less regular (Figure 8b). An decrease in regularity was observed as  $N_e$  increased towards 180. In contrast with the prediction of Hypothesis 1, 90 and 180 external ants actually enlarged the final nest size rather than shrank it, although the differences were small compared to experiments when the amount of



**Figure 9:** Difference between runs without and with pheromone building template in terms of a) average distance of stones from the middle of the cloud where a negative number indicates smaller nests in the template experiments and b) standard deviation of the number of stones in 8 conical sectors of the cloud where a negative number indicates more regular structures in the template experiments using  $N_e=10$  with  $\vartheta_{PM}=0.5$  (red) and  $\vartheta_{PM}=1.0$  (yellow).

internal ants or values of  $\vartheta_{PM}$  varied (Figure 7a). Details of this result can be found in the Discussion section.

Since the effect of pheromone concentration on stone dropping probability (Equation 4) was not switched on during these experiments, it can be concluded that the movement of ants itself was sufficient to explain creation of nests, the size of which varied with the colony size.

### 3.3. Pheromone building template

The effect of using pheromone to reinforce dropping as set by Equation 4 is depicted on Figure 9. The ants mostly tended to build smaller and more regular structures as dropping became more precisely timed and tied to an ant's location within the pheromone cloud. This effect was more significant

for larger colonies that moved more randomly.

Furthermore, the building dynamics were more interesting in the template experiments. In particular, when template was not used, 50 internal ants always started dropping stones where the final structure would appear. On the other hand, during template experiments with  $N_i = 50$ , stones were initially dropped in approximately the same distance from the brood cluster as with  $N_i = 30$  and the nest was expanded later as the ants kept frequently encountering stones, creating a pressure from inside of the walls.

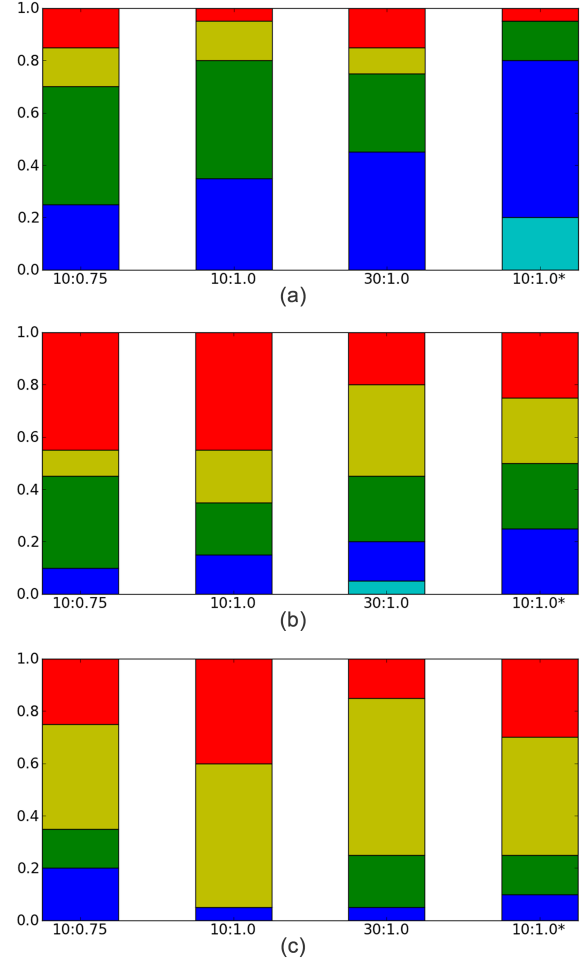
A minimal effect of pheromone during template experiments was observed in runs with 10 and 20 internal ants when  $\vartheta_{PM} = 1.0$  as the ants could not reach the areas of appropriate pheromone concentration. However, while 10 internal ants with  $\vartheta_{PM} = 0.5$  in non-template experiments tended to leave many stones in the middle of the cloud and thus failed to build nests, switching the template on resulted in more regular structures and also increased the average distance of the stones from the brood cluster. In this case, the pheromone building template made nest creation possible when it otherwise would not be.

### 3.4. Entrance Formation

Experimental runs were evaluated manually in order to categorise the final structures by the number of entrances they had and whether they could be considered nests at all (Figure 10). The most regular nests were built when 10 internal ants were used. Irregular nests occurred only 5% of the time when  $\vartheta_{PM}=1.0$  and 15% of the time when  $\vartheta_{PM}=0.75$  or when  $N_e=30$ . The amount of the most regular nests with only 1 or 2 entrances increased as the number of external ants increased and similarly when pheromone building template was used. However, in the latter case, the ants also built a complete wall around them with no entrances at all on 20% of occasions.

A similar pattern of entrance formation was observed in colonies with 30 internal ants, although generally the amount of irregular structures increased in comparison with the previous case. Furthermore, these colonies tended to build nests with 3 or more entrances more often, especially when  $N_e = 30$  (3 entrances created 25% of cases, more entrances in 35% of cases). A nest with 0 entrances was only built on one occasion, when  $N_e=30$ .

The trend to created more entrances was even stronger for colonies with 50 internal ants. This



**Figure 10:** Proportion of nests with 0 (cyan), 1 or 2 (blue), 3 (green) or more entrances (yellow) and irregular structures (red) using a)  $N_i=10$ , b)  $N_i=30$  and c)  $N_i=50$ . The individual groups are labeled using pattern  $N_e : \vartheta_{PM}$ . A star (\*) indicates that the template experiments.

was especially true when  $\vartheta_{PM}=1.0$ , in which case nests with more than 3 entrances formed 55% of the time. Interestingly, regularity of nests increased in comparison with colonies where  $N_i = 30$  ( $N_i = 30$  and  $\vartheta_{PM} = 0.75$  or  $\vartheta_{PM} = 1.0$ , regular nests occurred 55% of the time, while  $N_i = 50$ ,  $\vartheta_{PM} = 0.75$ , 75% occurrence and  $N_i = 50$ ,  $\vartheta_{PM} = 1.0$ , 60% of the time). The nest regularity increased slightly in the template experiments ( $N_e = 10$ ,  $\vartheta_{PM} = 1.0$  regular nests 60% of the time and 70% of the time in the template experiments), although regular nests were the most frequent when  $N_e = 30$  and  $\vartheta_{PM} = 1.0$  (85% of the time).



## 4. Nests of different shapes

Standard structures created by ants in a single pheromone cloud were circular. In the following set of experiments, the pheromone cloud diameter was decreased from 300px to 150px and a number of clouds with brood clusters at their centres were arranged in order to create nests of different shapes.

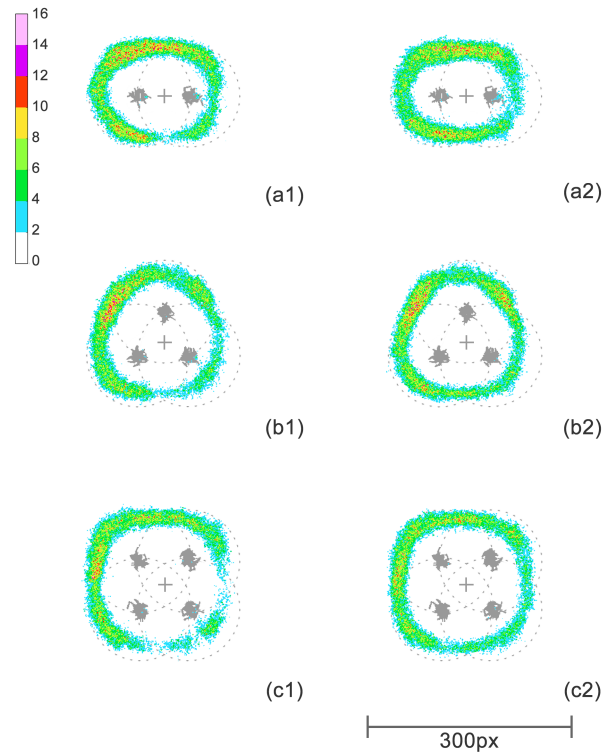
Three experimental setups were created: a) rectangle: two clouds were horizontally aligned and the distance of their centres was set to 75px, b) triangle: three clouds, the centers of which formed the vertices of a triangle with sides 75px long and c) square: four clouds centers of which formed corners of a square with 75px side length. The number of external ants was 10, while there were always 10 internal ants per pheromone cloud. The value of  $\vartheta_{PM}$  was set to 1.0, since the previous experiments showed that the most regular nests were built with this value (Figures 7 - 10).

The final pixel positions from 20 runs in each experiment were gathered together in order to form contour plots (Figure 11). After the rest of the arena was cleared of stones, a general desired shape was always achieved, although there were no sharp corners as walls naturally curved around boundaries of the individual pheromone clouds. Similar to all the other experiments, using the pheromone building template facilitated creation of more regular structures, although it was not required to achieve the desired shapes.

One or two entrances usually formed along the shorter edges of rectangular structures. The triangular nests had one to three small entrances that could be found near the vertices. Entrances in square nests were usually more numerous and formed both along the edges and in the corners. Probably due to their size, square structures had the least regular distribution of stones in their walls.

## 5. Discussion

Nest formation by simulated ants was tested in a number of different scenarios. The final circular structures, as well as the process by which they were built were comparable to real and previously simulated ants (Franks et al., 1992; Theraulaz et al., 2003) across a wide parameter space. Usually, the ants initially created a number of stone heaps that were gradually spread out and joined together, while the areas of future nest entrances remained clear



**Figure 11:** Contour plots of nests created during the a) rectangle, b) triangle and c) square experiments. Results from non-template (1) and template (2) experiments are shown. Pheromone clouds are represented by dotted circles. Brood clusters are shown in gray and crosses show arena centres.

throughout the process. Adding more external ants caused entrances to be initially created and destroyed and stable gaps in walls appeared only later in the simulations.

The building behaviour was more similar to behaviour of real ants that clear a cavity of stones and create a number of progressively joined heaps rather than of those that bring stones from outside of the building site and gradually form a C-shaped nest with only one entrance (Franks et al., 1992). It is possible that in the latter case, external ants carry stones from single location towards the nest rather than from all directions as was the case in the simulated arena, or that they find stones further away from the nest, causing a slower stone intake rate and thus different wall formation dynamics.

The nest size varied as the number of internal ants increased, confirming the assumption of Hypothesis 1 and of Franks and Deneubourg (1997), al-



though regularity of the structures decreased when they became large. The differences in nest size occurred due to variations in ant movement as large colonies required more space to spread out. Similarly, larger structures were formed when movement of ants within the pheromone cloud became less restricted by varying the  $\vartheta_{PM}$  parameter.

On the other hand, the assumption of Hypothesis 1 that larger numbers of external ants  $N_e$  would cause higher pressure and thus creation of smaller nests was only true when  $N_e$  increased from 10 to 30 (Figure 8). The nests actually became larger and less regular when  $N_e = 90$  and 180. The surprising increase in nest diameter occurred because more external ants could be found inside of the pheromone cloud, adding to the size of the physical template formed by the internal ants and brood. Nest regularity decreased as higher amounts of external ants cleaned the environment of stones quicker, which increased the probability of them reorganising heaps within the pheromone cloud and reinforcing thicker parts of already formed walls.

Using of the pheromone cloud as a template for building (Equation 4) improved the nest regularity (Figures 9, 10, 11). Furthermore, the resulting structures were smaller as the gradient of pheromone concentration interfered with the effect of ant movement, confirming Hypothesis 2. This effect could not be observed with 10 internal ants as they could not reach sufficient pheromone concentration values.

The fact that the pheromone template was not required for building of nests agrees with assumption of Franks and Deneubourg (1997) who understood pheromone as simply a cue for ants to orient themselves within the nest. The mechanism implemented by Theraulaz et al. (2003), where pheromone affected stone deposition, thus seems unnecessary and it appears that ant building cannot be directly compared to that of termites that actively use pheromone during building.

The assumption of Hypothesis 3 that nest entrances would form when ant movement is less random ( $\vartheta_{PM}$  is high) was partially correct (Figure 10). In the case when the number of internal ants  $N_i = 10$ , a higher amount of regular structures was produced for  $\vartheta_{PM} = 1.0$  compared to when  $\vartheta_{PM} = 0.75$ . However, the effect of  $\vartheta_{PM}$  was not apparent when  $N_i = 30$  and was reversed when  $N_i = 50$ . It seems that colonies of different sizes had different values of  $\vartheta_{PM}$  associated with the most regular nests. On the other hand, use of the pheromone

building template always improved nest regularity, as predicted.

Finally, it was shown that non-circular nest shapes can be created when multiple pheromone clouds are arranged together (Figure 11), as predicted by Hypothesis 4. The clouds needed to be small enough so that there was enough stones available to create the final shapes and also suitably close to each other so that internal ants could travel between them. The stone positions were slightly biased towards upper left corner of the arena, especially in the square experiments and when the pheromone building template was not used. A similar effect was observed for some larger circular structures. Careful inspection of the implementation code did not reveal any bugs and it is possible that the irregularities were a result of imperfections in Java's random number generator that movement of ants and initial positions of stones depended on.

This work has helped to understand the building behaviour of ant *Leptothorax tuberointerruptus* and answer questions about roles of colony size and the pheromone cloud in the building process. More importantly, it was shown that this simple algorithm could perhaps be applied with cheap robotic ants to create very simple structures of desired shapes. A more interesting applications that the author aims to look at are using principles like nest morphogenesis and agent-induced pheromone gradients in order to build more complicated heterogeneous structures.

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