

Measurement of Space: From Ants to Robots

Erol Şahin*

*IRIDIA

Université Libre de Bruxelles,
Avenue Franklin Roosevelt 50,
CP 194/6, B-1050,
Bruxelles, Belgium
esahin@ulb.ac.be

Nigel R. Franks**

**Centre for Behavioural Biology,
School of Biological Sciences,
University of Bristol,
Woodland Road, Bristol,
BS8 1UG U.K.
Nigel.Franks@bristol.ac.uk

Abstract

We are interested in the ways that animals use to measure spaces that are much larger than their sensing range, and how these ways can be tested and adapted by the mobile robots. Particularly, the animals that we are concerned are the scout worker ants that assess potential nest cavities needed by their entire colony. The individual scout ants work literally in the dark and the spaces that they explore are beyond their immediate sensing range and have irregular and unpredictable shapes. Furthermore, these scouts must not only measure the floor area of a potential nest site but they must also assess the integrity of the inner periphery of the nest to check that it does not have too many holes that would make it difficult to defend against enemies. The hypothesis that the scouts use a ‘Buffon’s needle algorithm’ to estimate the nest size is supported by experiments. In this paper, we present a behavioral model for the nest size assessment of the scouts. This behavior is implemented on an *ant-bot*, a simulated scout model, to study the assessment process. We present the simulation results obtained from this model by systematically varying the behavior and analyzing how well the size of the nest is evaluated and how well the integrity of the periphery is checked. We also discuss future lines of research on how the robots can be used for illuminating further the behaviour of the ants, and how these studies can be useful in developing robust behaviors for autonomous mobile robots.

1 Introduction

Behavioral Ecology and Autonomous Mobile Robotics have a lot to learn from each other. On one side, the science of Behavioural Ecology is concerned with the ways that organisms make adaptive decisions in their everyday lives. Such decisions, often involving choices among two or more alternatives, require the organism to assess

the quality of alternative courses of action based on its limited local sensing. “How do organisms make such assessments?” has been a fundamental question of Behavioral Ecology.

On the other side, the field of Autonomous Mobile Robotics aims to develop artefacts that can ‘survive’ the real world by making good decisions. The classical engineering methods are often inadequate for the design of systems that require reliable performance under the constraints of a mobile robot platform. In this sense, the question of “how can mobile robot systems make good assessments?” can be considered as fundamental one facing against its counterpart in Behavioral Ecology.

In this paper, we consider the nest assessment of ant scouts as an example of animals making complex measurements. The task is particularly interesting, since the animal must assess, among other factors, the size of the spaces with unknown shape, and are much larger than its perceptual range. The hypothesis proposed for the measurement of nest size is implemented on a simulated mobile robot. The simulation not only allowed us to test and analyze the hypothesis, but it also allowed us to vary the parameters of the constructed model to study the other varieties of the model that the evolution had not chosen.

2 Nest Assessment in *Leptothorax albipennis*

We study the behavior of a single scout worker from a colony of *Leptothorax albipennis* ants. Such scouts need to assess potential nest sites when the current nest of their colony is damaged or destroyed. They work on behalf of their colony, which may contain 200 or more workers. They need to reject nests that are not sufficiently large to house all of their nest mates. Hence they must measure the floor area of a potential nest site, that is usually hundreds of times larger than themselves, and check the integrity of its inner perimeter to ensure that the nest site is easy to defend against other ants.

Colonies of *Leptothorax albipennis* naturally occur in

thin fissures in rocks. Their nest sites are remarkably flat and can have very irregular internal perimeters. Studies have shown that individual scouts working alone make initial nest site measurements. Such scouts are literally in the dark and have no overview of the irregular cavity they must assess. Clearly, they have a very difficult problem to solve.

Mallon and Franks (2000) observed the visits of individual scouts to new sites in the laboratory, where the ants will readily nest in cavities between microscope slides. They reported that scouts tend to make more than one visit to a new site before attempting to initiate the emigration of their entire colony. During their visits, the scouts spent a considerable part of their time exploring the internal periphery of the site, while making seemingly random explorations of the central part of the nest, Fig. 1. Based on these observations and many others, they suggested that the scouts lay an individual-specific pheromone trail during their first visit, and that they use the intersection frequency of their path with this pheromone trail during their subsequent visits to estimate the floor area of the nest. They pointed out that, this strategy is consistent with the Buffon’s needle method, a technique in computational geometry to estimate π empirically, that can be adapted to measure space.

They tested this hypothesis by tracing the visits of scouts to five different potential nest sites in the laboratory environment. They counted the intersections of traces between the first and subsequent visits separately within the central region and the peripheral region of the new nests. The results confirmed that their Buffon’s needle hypothesis is plausible.

The key test of this Buffon’s needle hypothesis is to manipulate the intersection frequencies of scouts with their own trail to fool them into making inappropriate decisions. Because the trail pheromones are individually-specific it would be difficult to increase their abundance. However, it is possible to decrease their abundance, so that intersection frequencies are reduced. Doing this should cause ants to accept nests that are actually too small. Mallon and Franks (2000) did this with a so-called ‘magic carpet’ experiment. They gave colonies a binary choice between a full size (acceptable) nest and a half size nest that they should reject as too small. However, the small nest had an acetate sheet on it floor which could be removed between the scout ant’s first and second visit. This acetate sheet or ‘magic carpet’ had holes over half its area so that when it was removed only half of the trail laid by the ant on it first visit was removed. Hence, the ant should encounter an intersection frequency between its second visit and first visit path that would indicate a fully size nest. This seems to be the case, because in these choice experiments equal numbers of colonies choose the full size nest and the half size nests from

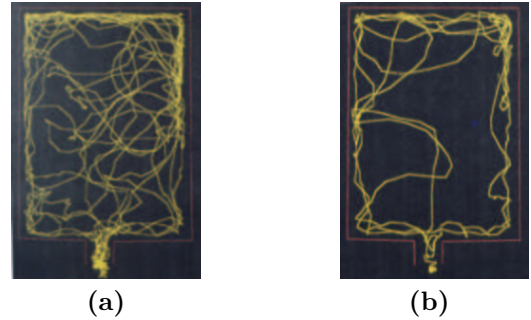


Figure 1: Two trails of a scout visiting a new nest site as traced by an overhead camera. (a) shows the trail of the first visit, (b) shows the trail of the second visit.

which magic carpets had been removed.

Further work by Mugford et al. (2001) looked at the quantity and quality of data individual scouts were potentially able to obtain from their own efforts when visiting nests of different size. These studies suggest that individual scouts should be able to obtain good data to implement the Buffon’s needle algorithm with the level of precision actually seen in nest choice experiments. This is painstaking work because all of the scouts from several different colonies had to be individually identifies with unique paint spots and each ant is only 2mm long! Scouts then had to be followed and their movements recorded in great detail as they assessed, on both their first and second visits, nests that were both large and small.

One among many issues that requires investigation is how the ant is able to check both the integrity of the internal periphery of the nest and its floor area. These measurements would seem to be in potential conflict. Measurement of area requires the ant to check regions of the nest away from its wall. Indeed, it may be possible that the pheromone trail at the periphery can cause problems for the implementation of ‘Buffon’s needle algorithm’.

This paper attempts to tackle these issues by constructing a simulation that mimics the environment, the ant and its behavior model for assessing new nests of various sizes and shapes. By varying a parameter of the exploration behavior, the simulation allowed us to study the dynamics of the assessment process for achieving an optimal assessment of a new nest.

In the rest of the paper, we will first present the model for the simulation of the ant and its environment. Second, we will describe the exploration behavior of the ant model proposed for nest assessment. Third, we will describe the experiments carried out and the results we obtained. Finally, the results are discussed and future directions for the work are outlined.

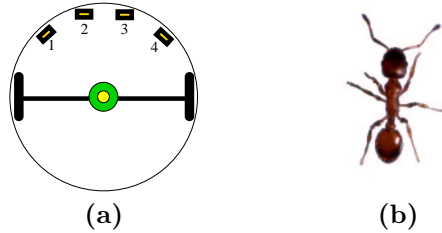


Figure 2: **(a)** The ant-bot is sketched. The circle represents the body. The two vertically elongated rectangles placed on the left and right part of the body denote the wheels of the robot. The four small boxes on the upper part of the figure shows the placement of the infrared proximity sensors. The concentric circles drawn at the center of the robot indicate the pheromone nozzle and detector. **(b)** *Leptothorax albipennis*.

3 Simulation

A free mobile robot simulator, YAKS¹, is modified to study the nest assessment process ant scouts. The simulator is designed to simulate a physical mobile robot, Khepera (Mondada et al., 1993) (K-Team, Switzerland), in 2-D by sampling the sensory readings from a real robot (Miglino et al., 1995). The use of a mobile robot simulator allowed us to model the interaction between the scouts and the environment in a more realistic way.

3.1 The Ant-bot

We modeled a scout ant in the form of an *ant-bot*, sketched in Fig. 2-(a). The original Khepera robot model of the simulator is modified for this purpose. The ant-bot has four infrared proximity sensors placed in the front to imitate the short-range sensing ability of the ant with its movable antennas, Fig. 2-(b). A “pheromone nozzle” and a “pheromone detector”, shown as concentric circles at the center of the body, are added to the ant-bot to model the pheromone laying and smelling ability of the scouts.

3.2 The Nests

Five different nest designs, are shown in Fig. 3. These nests are created by walls as a closed rectangular space. Unlike the real nests, used in the experiments of Mallon and Franks (2000), the entrances are omitted to remove the possibility of the ant-bot leaving the nest prematurely. The small rectangle shown under the nest, marks the position of the entrance. Within the environment the ant-bot is drawn as a circle with a line connecting its right and left wheels.

The nest in Fig. 3 (a), shows the standard size nest used in our experiments. The nest in (b) is a standard size nest with a partial barrier placed at the center of the

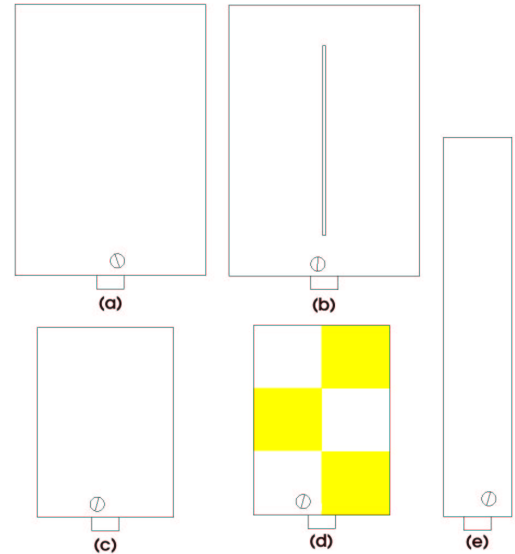


Figure 3: The five types of nests considered for the experiments: **(a)** the standard size nest, **(b)** the standard size nest with partial barrier, **(c)** the normal half size nest, **(d)** the half size nest with ‘magic carpet’ and **(e)** the half size thin nest.

nest. The nests in (c,d) have half the size of the standard size nest. Although the nest shown in (e) has the same size as the nests in (c,d) its perimeter is twice as long as them. The nest in (d) has the ‘magic carpet’ on its floor, that was discussed in Sec. 2. The gray regions in the nest, marks the regions where the pheromone trails of the ant-bot are cleaned before the second visit of the ant-bot.

4 Nest Assessment by the Ant-bot

Two visits are made by the ant-bot to a new nest. In each visit, it starts its exploration above the entrance at a random alignment. During the first visit, it lays pheromone along its path. During its second visit, instead of laying pheromone, the ant-bot senses the pheromone layed during its first visit, and uses this information to estimate the size of the nest. In both visits, the ant-bot uses the same exploration behavior.

The exploration behavior uses the infrared proximity sensors to drive the ant-bot creating exploration trails that seem similar to those observed in ant scouts. The behavior is parametrized in such a way that it can generate a continuum of trails that can range from wall following to random exploration.

4.1 Exploration Behavior

The exploration behavior uses the readings obtained from the four infrared proximity sensors to drive the two motors. The ant-bot is controlled by setting the speed

¹Available at <http://www.ida.his.se/ida/~johanc/yaks/>

of its left and right wheels (m_l and m_r), which are calculated as

$$\begin{aligned} m_l &= (1 - |\bar{r}|) * 0.25 - \bar{r} \\ m_r &= (1 - |\bar{r}|) * 0.25 + \bar{r}. \end{aligned}$$

When $\bar{r} = 0$, the ant-bot moves forward. It turns left when $\bar{r} = 1$, and right when $\bar{r} = -1$. Here, \bar{r} is defined as

$$\bar{r} = \begin{cases} -1 & : r + n < -1 \\ r + n & : -1 < r + n < 1 \\ 1 & : r + n > 1 \end{cases}$$

where n is a random number between -0.4 and 0.4 and r is defined as the value of the ‘rotational activation’. The change in r is calculated as

$$\begin{aligned} \Delta r &= -0.9r + 0.3(1 - r)(w_l + 1.5I_4 + 1.2I_3) \\ &\quad - 0.3(1 + r)(w_r + 1.5I_1 + 1.2I_2) \end{aligned}$$

where I_i denotes the infrared readings, with a value between 0 (no object) and 1 (very close object), where $1 < i < 4$ is the index. Here, w_l, w_r represent the ‘perceived presence’ of the wall on the right and left side respectively. The first term on the right of the equation guarantees that when no wall is perceived and the infrared readings are all zero, then any rotational activation will decay to zero in time. The second term raises the rotational activation towards 1 in proportion to the amount of wall perceived on the left side and the infrared readings from the right side. The third term tries to pull down the rotational activation to -1 in a similar way.

The variables, w_l and w_r , indicate the presence of the wall on the left and right side of the ant-bot respectively and the change in them are defined as

$$\begin{aligned} \Delta w_l &= -0.1w_l + \gamma(1 - w_l)I_1 - 0.7w_l(I_2 + I_3) \\ \Delta w_r &= -0.1w_r + \gamma(1 - w_r)I_4 - 0.7w_r(I_2 + I_3). \end{aligned}$$

The first term on the right side causes the perceived presence of a wall to decay to zero when no objects are sensed. The second term, increases the perceived presence of the wall by the activations of infrared sensing on that side. The third term diminishes the perceived presence of any wall, if the front sensors become active, to raise the priority of avoidance. The parameter γ controls the perceived presence of the wall. When the parameter $\gamma = 0$, both w_l and w_r decay to zero, and stay there. For nonzero values of γ the perceived presence of wall becomes stronger.

The exploration behavior defined above can generate exploration patterns ranging from random exploration, to wall following, by varying γ . When $\gamma = 0$, the wall sensing part of the behavior is removed, and the robot moves in a random way, while avoiding any obstacles on its way. As γ is increased, the wall sensing becomes active creating a attraction towards the wall. As the attraction grows larger, the robot tends to stay closer to

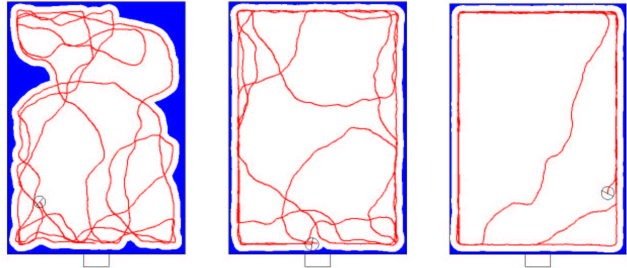


Figure 4: Different trails can be obtained by varying γ . Three trails from the exploration of a standard size nest for 10000 time steps, are shown. These trails are obtained for $\gamma = 0.0, 0.3, 1.0$, from left to right. Increasing γ beyond 1 tends to make the attraction towards the wall so strong that it may overcome the obstacle avoidance component of the behavior, causing the ant-bot to crash into the walls. The uncovered periphery is marked as a dark region inside the walls of the nest.

the walls and become less likely to move into the central part of the nest. Figure 4 shows three different exploration patterns achieved by different values of γ .

4.2 Evaluating the nest assessment

The assessment of a nest by the ant-bot is evaluated, using two measures: namely, how accurate the floor area is estimated, and how well the integrity of the nest perimeter is checked.

4.2.1 Measuring the size of the nest:

The size estimation is done by the ant-bot. The pheromone sensor, denoted as p , returns 0 or 1 reporting the absence or existence of pheromone under the ant-bot. This reading is processed by leaky-integrator:

$$\dot{\bar{p}} = -\alpha\bar{p} + (1 - \alpha)(1 - \bar{p})p$$

that generates a smoother sensory signal, with $\alpha = 0.1$. The Buffon’s needle algorithm is approximated, by counting the rising edge crossings of this signal with a threshold of 0.5. In the rest of the article, we will use the term ‘Buffon count’ to denote the number of these crossings counted during the second visit of the ant-bot.

4.2.2 Measuring the periphery coverage:

The quality of the ant-bot’s periphery check, is defined as the area between the inner region covered by the pheromone trail of the ant-bot and the periphery. This evaluation is done by the simulator after the first visit of the ant-bot. The dark regions between ant-bot’s trail and the inner periphery, Fig. 4, shows the checked periphery for three different explorations.

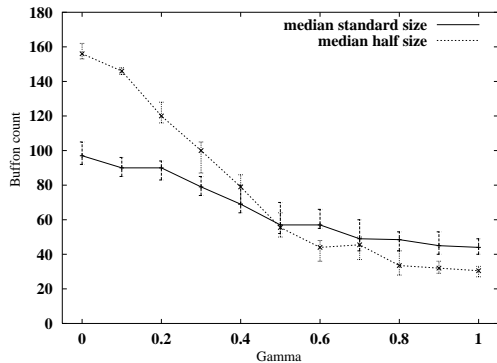


Figure 5: Median Buffon count for standard and half size nests. Error bars indicate the inter-quartile interval of the data.

5 Results

The five nest types, shown in Fig. 3 are used in the experiments. For each nest type, the ant-bot made two visits to the nest: the first, lasting for 10000 time steps; the second, lasting for 7500 steps. In each visit, the ant-bot began its exploration in front of the entrance, which is indicated by a small rectangular block below the nest. The initial position of the ant-bot was kept constant except that its initial orientation was varied within ± 15 degrees of the wall.

We have evaluated the nest size estimates of the ant-bots, and the amount of uncovered periphery while varying γ from 0 to 1. For each value of γ , approximately 20 nest assessments are done by the ant-bot.

Figure 5 plots the median Buffon count for the standard and half size nests, with respect to γ . The error-bars mark the interquartile interval of the data. The plot clearly shows that, even with the Buffon's algorithm in operation at the periphery, where trails are less random, for $\gamma < 0.3$, the ant-bot can reliably distinguish between a standard size and half size nest. It should be noted that, at high γ values, the Buffon count in the half size nest dips below the Buffon count of the standard size nest. This is due to the fact that the pheromone trails get 'crowded' at the periphery, blending into fewer thicker trails. In the half size nest, the ant-bot has the time to make more 'rounds' causing more blending than the standard size nest, hence resulting fewer Buffon counts.

Figure 6 plots the median percentage of covered periphery with respect to γ . It can be seen that, as expected, the amount of covered periphery increases with γ . Note that this result confirms our intuition that the periphery checking task in conflict with the accuracy of the size evaluation.

Figure 7 plots the normalized median and the interquartile values of the Buffon counts obtained from different types of nests while varying γ . The normalization is done by dividing all the median and interquartile

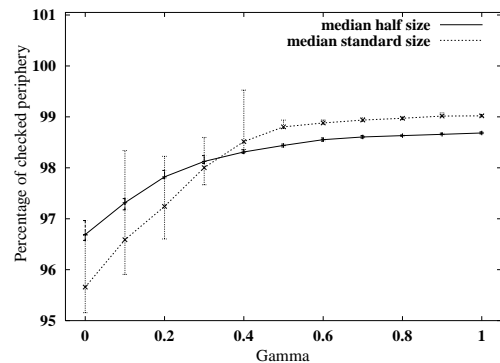


Figure 6: The percentage of covered periphery. Note that the percentage of the covered periphery will always be less than 100 since the body of the ant-bot does not touch the periphery. Error bars indicate the inter-quartile interval of the data.

values with the median Buffon count of the standard size nest for that particular γ value. The plot in (a) shows the normalized median values for the standard size nest, all being 1, and for the normal half size nest with their normalized interquartile bars. The shortness of the interquartile bars confirm the conclusions of Mugford et al.'s (2001), that the Buffon count method provides a rather accurate estimate of the nest size, for $\gamma < 0.3$. The plot in (b) clearly shows that, the partial barrier placed inside a nest has no significant affect on the size measurement. The plot in (c) shows that the thin half size nest generates approximately the same number of Buffon counts as the normal half size nest. This result is in accordance with Mallon and Franks' results confirming that the perimeter length does not affect the algorithm. The plot in (d) shows the normalized Buffon counts of the 'magic carpet' nest. Note that the Buffon counts are almost halved due to the removal of traces from half of the nest after the first visit. Note that even for $\gamma < 0.3$, the values indicate a larger nest than the standard size nest. At the first glance this result may seem to be in conflict with those that are reported in (Mallon and Franks, 2000), where the standard size nest was preferred over the 'magic carpet' nest 12 times in 20 experiments. One possible explanation for this experimental result is that the scouts may have rejected the 'magic carpet' not because it was smaller but because it was larger than their preferred nest size! Mallon and Franks (2000) have indeed reported that nests larger than the preferred size can be rejected as well. Another possible explanation can be that the removal of the pheromone trails at the periphery if the 'magic nest' may be rejected since it failed for the integrity of the periphery.

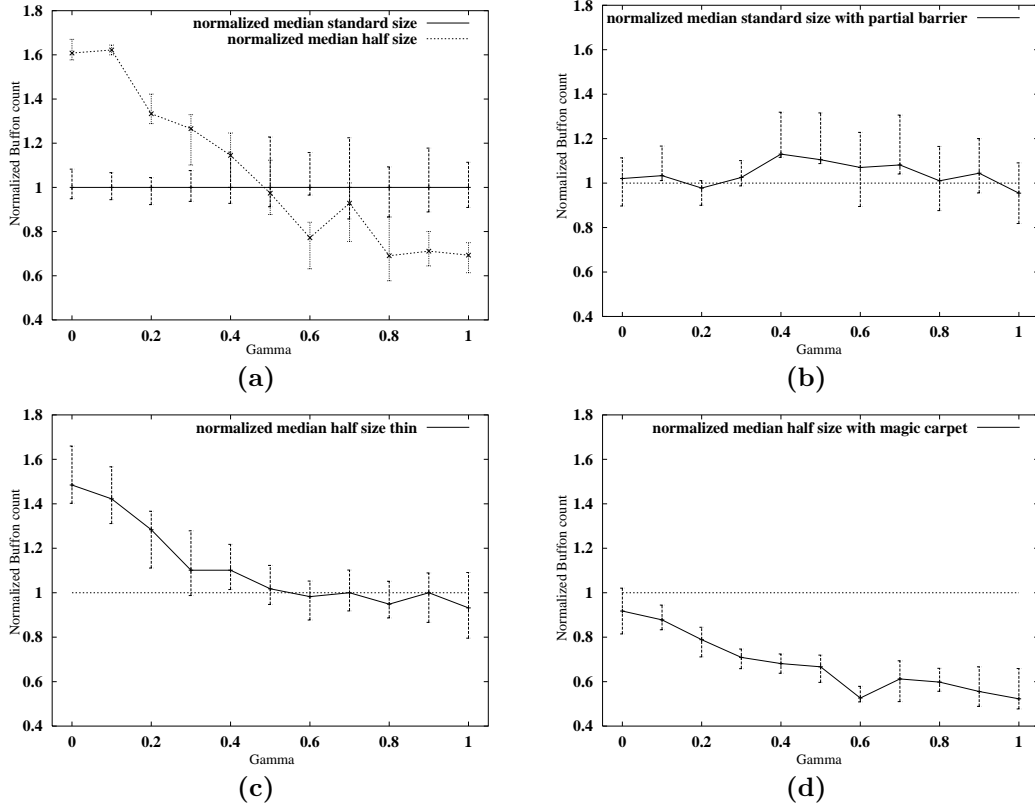


Figure 7: Normalized Buffon counts for different nests. Error bars indicate the inter-quartile interval of the data.

6 Conclusions

We proposed a model of nest assessment in scout ants. The model shows that an exploration behavior that combines obstacle avoidance and wall following, with the addition of a high amount of noise, is sufficient both to generate similar trails to those of the real ants and to enable them assess a nest site accurately. The analysis shows that the exploration behavior has to be tuned to optimize the nest assessment.

7 Future lines of Research: Collective decision-making in ants and robots.

Although all the measurements we have described are made by individual ants, the final choice of a nest site also involves social decision-making. When an individual ant has made all of its measurements of a new nest site it may decide to accept it or reject it. Acceptance is followed by nest-mate recruitment. If it accepts a nest, it begins to recruit its nest-mates from the old destroyed nest to the new one. Most intriguingly, such a scout typically recruits its new nest-mates initially by the very slow method of leading them one by one to the new nest site. This so-called tandem running is excruciatingly slow. However, such tandem-running recruitment

is followed by a vastly faster form of recruitment that simply involves the ant carrying its nest-mates to the new nest site. Such carrying behaviour is almost exactly 3 times faster than tandem running.

Why do the ants use slow tandem-running when they could immediately begin using much faster carrying behaviour that seems to be 3 times more efficient? First, in tandem running the ant being lead can learn the way to the new nest so that in turn it can also become an active recruiter. Second, slow tandem running provides a time lag in which news of a better nest site might have time to arrive at the old nest site.

What causes individual scout ants to switch between slow tandem running and fast carrying behaviour? This is an important switch because carrying behaviour is so fast that a nest so favored is likely to out compete an even better nest sites that is discovered too late. The answer to the question - What throws this switch? - is a fascinating one. Scouts effectively use opinion-polling based on quorum-sensing to decide when to recruit at top speed. Pratt et al. (2002) have shown that the switch from slow tandem-running to fast carrying is associated with scouts encountering between about 9 and 17 of their nest-mates in the new nest site. This threshold number of nest-mates is in effect allows for opinion-polling. Not only does the individual scout deem the new nest site

suitable but so apparently do a good number of its nest-mates. Typically, an individual scout only leads a few tandem runs, so many of the 9 to 17 nest-mates will have arrived at the new nest site either "under their own steam" or they will have been lead there by another scout. So this quorum-threshold will indicate that many ants independently hold a good opinion of the new nest site.

In future, it will be fascinating to explore the use of such social behaviour in complex measurements and decision-making. We will plan to use societies of robots better to understand societies of ants. In turn, these insights should favor new an unexpected technological lessons for robotics.

8 Acknowledgements

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