Blind Area Measurement
with Mobile Robots

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Abstract

We are interested in the problem of how a mobile robot can measure the area of a closed region that is beyond its immediate sensing range. Our inspiration comes from scout worker ants who assess potential nest cavities. These scouts work literally in dark to assess arbitrary closed spaces. Experimental studies have shown that the scouts can reliably reject nest sites that are small for the colony. These studies support the hypothesis that scouts use the "Buffon's needle method" to measure the area of the nest. We have implemented the Buffon's needle method on a simulated mobile robot system and evaluated its performance through systematic experiments. The results show that the method can reliably measure the area of closed regions regardless of their shape and compactness, and that the method is undisturbed by partial barriers placed inside these regions.

Contents

1 Introduction

Insect studies uncover fascinating examples for autonomous robotics on how, seemingly difficult, problems can be solved through simple behaviors. Based on their observations, biologists make hypotheses about the methods implemented by these simple behaviors. Although these hypotheses are usually tested against experimental data collected from insects, they still beg a constructivist analysis. By constructing behaviors that implement these hypotheses on physically embodied systems, autonomous robotics can not only serve as a testbed for biology, but can also accomplish "technology transfer", adapting these solutions to artificial systems.

In this paper, we study how a mobile robot can measure the area of a closed region that is beyond its immediate sensing. We call this, as the problem of *blind area measurement* since it resembles to the challenge faced a blind person (lacking a complete view of the region being measured) trying to estimate the area of a large room using his hands (short-range sensing) only. Here, the term blindness denotes that the person (agent) cannot "see" the whole region (either because it is too large or because of objects that occlude a complete view) and that he has to use only his local and short range sensing abilities.

There have been quite a number of studies[1, 2, 3] on area coverage of arbitrary closed regions by robots. However, to the best of our knowledge, the question of how the areas of such regions can be measured has not yet been addressed.

In the rest of the paper, we first describe the nest assessment (where the area of the nest is one criteria) behavior of ant scouts, briefly summarize the experimental results and present the Buffon's needle hypothesis. Then we describe the experimental setup and the implementation of the Buffon's needle method on a simulated mobile robot. Section 5 describes the experiments conducted and presents the results. In the last section, we summarize the arguments supported by the experiments, and outline future directions for the research.

2 Nest Assessment in *Leptothorax albipennis*

Colonies of *Leptothorax albipennis*, a small monomorphic myrmicine ant species, inhabit small flat crevices in rocks. When the current nest becomes uninhabitable, the scouts explore the environment to find and assess new nest sites. These ant scouts assess potential nest sites before they attempt to initiate an emigration of the whole colony. Mallon and Franks[4, 5] observed the visits of individual scouts to new sites. They have 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. No significant differences were found between the duration of the first (second) visits to nests of different sizes[5]. It is also observed that in their second visits, the scouts "briefly but significantly slow down" as they cross their first visit trails. Based on these observations and many others, Mallon and Franks[4] suggested that the scouts lay an individual-specific pheromone trail during their first visit, and that they use the inter-
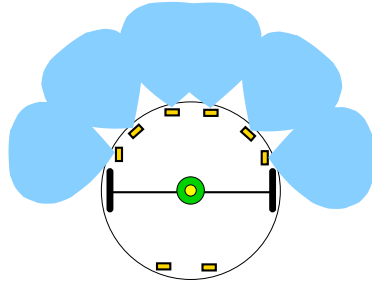
Figure 1: Sketch of the Khepera robot model. The circle represents the body. The two elongated rectangles placed on the left and right part of the body denote the wheels of the robot. The small rectangles around the body shows the placement of the infrared proximity sensors. The blobs emanating from the six front sensors (the two sensors placed at the back are not used) show the approximate sensing range. The concentric circles drawn at the center of the robot indicate the pheromone nozzle and detector.

section 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 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 obtained were consistent with the Buffon's needle method. Apart from the Buffon's needle method, they have also tested whether the ants use the internal perimeter of the nest, and the 'mean, free-path-length algorithm' to assess the size of the nests. However, the experiments showed that (1) scouts were able to choose a standard-size nest over a half-size one with the same internal perimeter and, (2) a partial barrier placed inside a standard-size nest did not affect the assessment of the nest.

In previous works[6, 7], we proposed that exploration behavior of the scouts contained at least two sub-behaviors; wall following and random exploration. We then constructed a mobile robot simulation through which we had studied the dynamics of the nest assessment process and proved that the two sub-behaviors were conflicting; that is the wall following behavior improves the periphery checking of the nest while impairing area measurement, whereas the opposite being true for the random exploration behavior. In this work we evaluate the Buffon's needle method as a blind area measurement method for mobile robots.

3 Experimental setup

We have chosen Webots (Cyberbotics, Switzerland) as the robotics simulator and used a robot model which simulates the Khepera[8] miniature robot (K-Team, Switzerland), by sampling the sensory readings from a real robot[9]. The robot has eight infra-red distance sensors as sketched in Fig. 3, however only the six sensors placed in the front are utilized. The robot is also equipped with a "pheromone nozzle" and a "pheromone detector", both located at the center of the body, the former for laying and the latter for detecting the pheromone in the simulated environment.
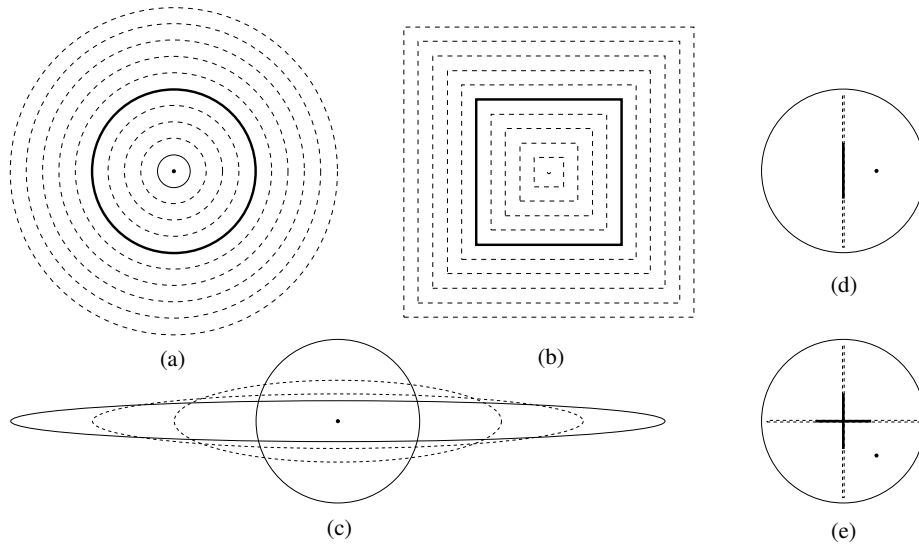
Figure 2: Five set of nests used in the experiments: **(a)** circular nests, **(b)** square nests, **(c)** elliptic nests, **(d)** standard size nests with vertical barrier, **(e)** standard size nests with cross barriers. The dark circles placed in the nests indicate the relative size of the robot.

3.1 The Nests

Five different set of nests, shown in Fig. 2, are used in the experiments. Unlike real nests, used in the experiments of Mallon and Franks [4], the entrances are omitted to remove the possibility of the robot leaving the nest prematurely. In each visit, the robot began its exploration from the central bottom part of the nest. The initial position of the robot was kept constant except that its initial orientation was varied within ±15 degrees of the wall.

Figure 2 (a), shows the circular nests used in our experiments. The diameter of the smallest circular nest is approximately ten times the body length of the ant-bot. The largest nest is ten times wider than the smallest one, and other eight nests have sizes in between. Circular nest with diameter 100 *units* (robot diameters) is taken as the standard size nest. Ten square nests in (b) are selected in such a way that area of each square nest is equal to the area of its circular counterpart. Figure 2 (c), shows the standard size nest and three elliptical nests having same area as the standard size nest but with different eccentricities (0.968, 0.994, and 0.998 respectively). The nests in (d,e) are standard size nests with | and **+** type partial barrier placed at the center. The length of the barriers (in horizontal and vertical directions) is varied.

3.2 Exploration Behavior

Using the six front sensors we designed an exploration behavior that is modified from the ones implemented in our earlier works[6, 7]. The behavior lies within the spirit

of Braitenberg's behaviors[10] with noise added to motor activations and short-term time dependency included to avoid abrupt changes in robot's movement. Details of the implementation of the exploration behavior is given below.

The ant-bot is controlled by setting the speed of its left and right wheels (m_l and m_r), which are calculated as

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

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

$$\bar{r} = \begin{cases} sign(w_r - w_l) * \bar{n} & : & \sum_{i=1}^{4} I_i > 2.7 \vee I_0 > 0.95 \vee I_5 > 0.95 \\ -1 & : & r + n < -1 \\ r + n & : & -1 < r + n < 1 \\ 1 & : & r + n > 1 \end{cases}$$

where n is a random number between -0.4 and 0.4, $\bar{n}$ is a random number between 0.3 and 1.0, w_l, w_r represent the 'perceived presence' of the wall on the right and left side respectively, r is defined as the value of the 'rotational activation', and I_i denotes the infrared readings, with a value between 0 (no object) and 1 (very close object), where $0 < i < 5$ is the index. The change in r is calculated as

$$\Delta r = -0.9r + 0.3(1 - r)(w_l + 1.5I_4 + 1.2I_3) - 0.3(1 + r)(w_r + 1.5I_1 + 1.2I_2)$$

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 peripheral wall on the left and right side of the ant-bot respectively and the change in them are defined as

$$\Delta w_l = -0.1w_l + \gamma(1 - w_l)I_1 - 0.7w_l(I_2 + I_3)$$
$$\Delta w_r = -0.1w_r + \gamma(1 - w_r)I_4 - 0.7w_r(I_2 + I_3).$$

The first term on the left 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 peripheral 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. Even with obstacle avoidance in place, the ant-bot can occasionally hit them and get stuck, particularly when its is moving straight towards the wall. The first condition of $\bar{r}$ allows ant-bot to escape from such situations by making steep turns away from the obstacles blocking its course of movement.
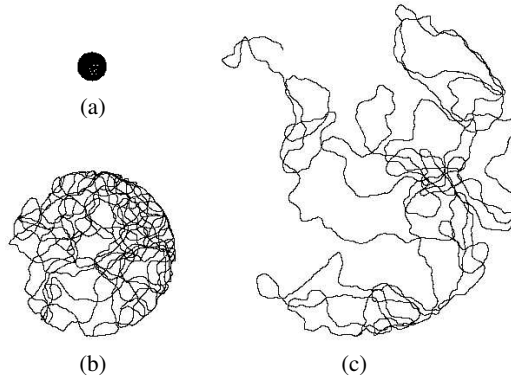
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Figure 3: Exploration patterns generated by the behavior for circular nests of **(a)** the smallest size, **(b)** the standard size, and **(c)** the largest size.

The exploration behavior generates random exploration patterns within a closed region. The robot moves in a random way, while avoiding any obstacles (walls or barriers in our experiments) on its way, covering the whole nest over the long run. Figure 3 shows exploration patterns for three different circular nests.

Braitenberg's original obstacle avoidance algorithm moves the robot like a ping-pong ball in the environment, driving it on almost straight lines in free space and bouncing from the objects like a ball. As a result the exploration trails tends to concentrate on certain bands in the environment and therefore is not very suitable for the Buffon's algorithm.

4   Buffon's needle method

The robot makes two visits to a nest using the exploration behavior described above. In each visit, it starts its exploration from the central bottom part of the nest at a random alignment. It lays pheromone along its path during its first visit. During its second visit, instead of laying pheromone, the robot senses the pheromone, and counts the number of intersections with the pheromone trail layed during its first visit. The output of the pheromone sensor (a binary value) is first filtered by a leaky integrator to remove any artefacts that may have occurred due to a pixellized implementation of the pheromone trail and then thresholded. *Buffon's count* is defined as the number of crossings counted during the second visit.

For a given nest, three parameters affect the Buffon's count: 1) the length of the first, 2) the length of the second visit, and 3) the thickness of the pheromone trail. For the experiments reported below, unless otherwise stated, the duration of the first visit is fixed to 50000 steps (the resulting trail length has a mean of 1680, and a variance of 0.76 units), and the width of the pheromone is taken as 0.1, i.e. one tenth of the body length of the robot. In order to discount the effect of the second visit, we define *normalized Buffon Count* (nBC) as the Buffon count normalized by the length of the

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second visit (which was also fixed to 50000 steps). In the rest of the discussion nBC is used as a measure for the area of the nest.

5 Experimental Results

Using the experimental setup and Buffon's needle implementation described in the previous section we have conducted systematic experiments to evaluate this method for blind area measurement. We have measured nBC 100 times for each of the nests shown in Fig. 2.

5.1 Shape

Figure 4 plots the median nBC value obtained from different sizes of circle and square nests (Figure 2 (a,b)). In (a), median nBC values measured from circular and square nests are plotted side-by-side for different sizes. Four points worth mentioning: 1) nBC values for square and circular nests are approximately the same for all sizes. The nBC values of circular nests are plotted against median nBC of square nests in (b). As it can be seen clearly, most of the points lie on the $y = x$ line showing that nBC is a good measure of area for circular and square shaped nests. 2) The error bars are small, showing that nBC provides a robust measure for area. 3) nBC values of the two smallest nests (with area 348 and 1392 $unit^2$) are lower than expected. One would have expected nBC be larger for smaller nests. This artefact is due to the blending of the pheromone trails into each other at the periphery as can be seen in Fig. 3(a). Since the trail density at the periphery is different for square and circular nests (due to the interaction between the boundary and the robot as produced by the exploration behavior), the amount of blending is different. As a consequence of the nBC values for these two nest sizes show more discrepancy, which is marked by two slightly off-axis points in (b). 4) Regression analysis show that there is a logarithmic decrease of nBC with area.

5.2 Compactness

In the experiments reported above, we have shown that nBC promises itself as a good measure for area. In order to evaluate the effect of compactness of the shape, we evaluated nBC for the set of nests shown in Fig. 2(c), where the elliptic nests cover the same area as the standard circular nest.

Figure 5.2 plots the median nBC values for the nests with respect to compactness value defined as r_1/r_2 where r_1 and r_2 denote the large and small radii of the ellipse. The baseline denotes the median nBC value for the standard circular nest with compactness $r_1/r_2 = 1$.

The plot shows that nBC values remain approximately the same despite the change in the compactness of the nest. As the nest becomes less compact, the variance in the nBC values increase (indicated by the growth in the error bars) also affecting the median value.

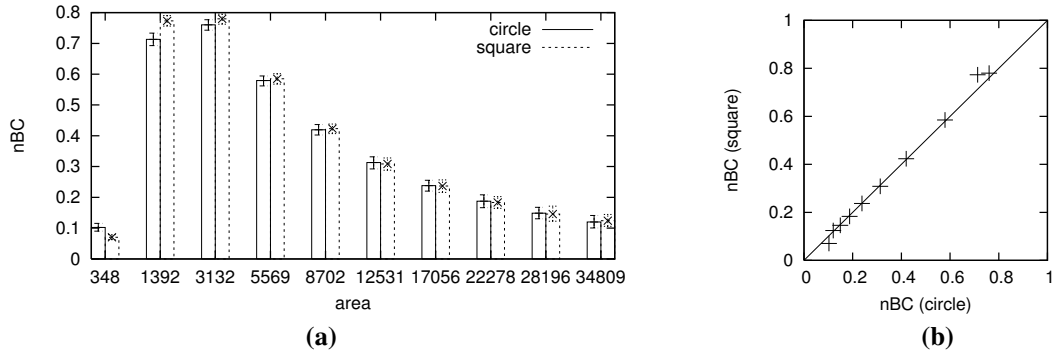(a)   (b)

Figure 4: **(a)** Median nBC values measured from circular and square nests are plotted side-by-side for different sizes. The error bars drawn indicate the interquartile range for the nBC values. **(b)** The nBC values of circular nests are plotted against median nBC of square nests.
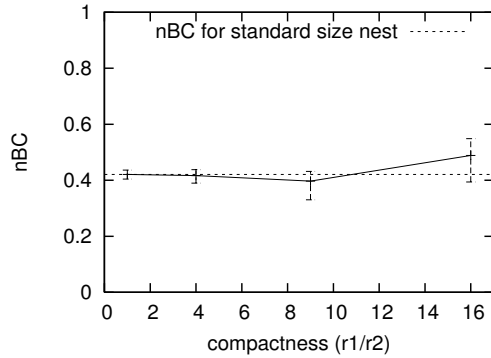

Figure 5: Median nBC values versus compactness (r_1/r_2). The error bars indicate the interquartile values.

5.3 Barriers

The experiments reported so far have used convex nests. In order to analyze the affect of non-convexity, we modified the standard circular nest by placing | and **+** type partial barriers varying at length at the center, as shown in Fig. 2(d,e).

Figure 6 plots the median nBC with respect to varying barrier length (percentage of the nest diameter) for both types of barriers. Again, the baseline denotes the median nBC value for the standard circular nest with no barriers. The plots clearly show that, the partial barrier inside a nest has no significant affect on the size measurement. The slight increase in nBC is possibly due to the non-zero size of the barriers. Although the barriers, themselves, do not take up much space, the robot's exploration behavior tends to keep the robot "a sensing distance away" from the barriers, hence shrinking the area being explored.

We should note that, as the openings between the barriers and the walls reduce down to a couple of robot's diameter, it becomes more difficult for the robot to pass from one lobe to the other causing the robot to remain stuck in some of the lobes. As a
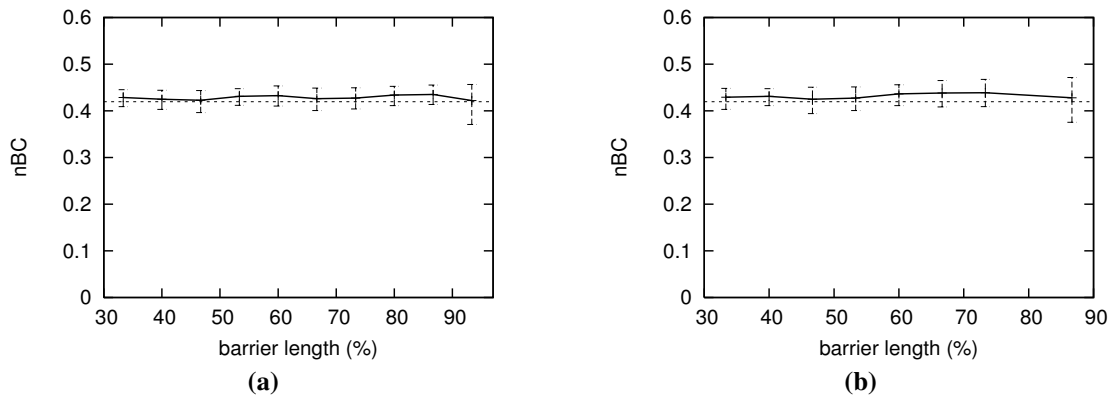
Figure 6: Median nBC values versus barrier length (percentage of the nest diameter) is shown for nests with **(a)** | and **(b) +** barriers. The error bars indicate the interquartile values.
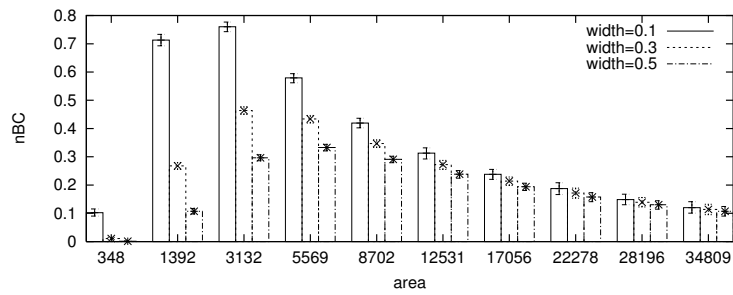

Figure 7: Median nBC values measured from circular nests are plotted side-by-side for different thickness of the pheromone trail. The error bars drawn indicate the interquartile range for the nBC values.

result of this, the variance the error bar corresponding to the the largest barrier length is increased.

5.4 Pheromone thickness

As mentioned before, the thickness of the pheromone trail being laid can affect the value of nBC. Figure 7 plots the median nBC values of circular nests for different pheromone thickness values. It can be clearly seen that as the thickness of the pheromone increases, blending (which can be seen by smaller-than-expected nBC values for small nests) affects larger nests.

6 Conclusions

In this paper we evaluated the Buffon's needle method as a blind area measurement method using mobile robot simulations. We have conducted systematic experiments and analyzed the performance of the method. The results obtained indicates that the Buffon's needle method provides a very powerful, and robust way to measure closed regions. nBC is a good measure for the area of closed regions. Also;

- nBC seems to be independent of the shape. However, we agree that, more experiments and analysis need to be done before coming to clear conclusion.

- nBC is independent of the compactness of the nest.

- nBC is independent of the barriers (or objects) placed inside the nest.

The Buffon's needle is a promising area measurement method. However, as it is, there are many open questions that needs to be investigated: How invariant is nBC to more complex, and realistic shapes? How should the length (duration) of the first visit determined for maximum robustness? Can the first visit duration be determined on-line, that is during the visit? How can the Buffon's needle method be improved by making the exploration behavior influenced by the pheromone that was laid before?

7 Acknowledgements

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