Blind bulldozing: Multiple robot nest construction

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Blind Bulldozing: Multiple Robot Nest Construction

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***Abstract*— In this paper, we present a collective, or swarm construction algorithm to control robotic bulldozers in the creation of a work site. Predictions about robotic missions to the planet Mars have described such site preparation as essential to the success of later mission objectives, such as the construction of solar arrays, etc. This algorithm was based on a behaviour observed in a particular species of ant called "blind bulldozing." We developed a mathematical model of blind bulldozing using a unique approach based on Markov chains. Robot bulldozers were developed and used to test the algorithm in our laboratory. The team of robots was found to be successful at clearing an open area out of a field of rocks. Our robots' behaviour also agreed with the predictions of our model. This work is significant because it demonstrates the viability of blind bulldozing and represents the first time, to our knowledge, that a multiple robot system has carried out a form of the general construction task outside of simulation.**

I. INTRODUCTION

NASA envisions robotic missions to Mars that will use teams of multiple robots for such tasks as "terrain conditioning and site preparation" [4]. Site preparation is the process of clearing away rubble and debris from a specified area so that other operations may proceed there. Nature has provided us with a suitable algorithm for these tasks in the form of an ant nest building strategy that has been described as "blind bulldozing" [3]. In this paper, we present a mathematical model of this collective construction algorithm and implement such a system with a team of robots.

A. Background

Collective robotic construction is construction that is carried out by a group of robots. There are two basic approaches to construction. The first strategy views construction as the accumulation of material. Collective construction along these lines was described in [9], where software "wasps" wandered about a virtual nest, adding material in an orderly fashion. The "wasps" recognized specific environmental configurations which signaled where to place material. Intricate structures were produced using this strategy in simulation. This style of construction lends itself to applications where precision is required. In [10] a collective system successfully built thin brick walls in this way.

The second collective construction strategy is typified by the removal of material. It is this approach that solves the site preparation problem outlined in [4]. The object under construction is carved out of an overabundance of material. Often, the first step in construction is to clear out a foundation. Franks et al. discovered a cooperative nest building behaviour in a species of ant that carried out this sort of operation [3].

What makes these ants interesting to us is that the nests that they built were open regions cleared out of rubble. The ants implemented their own version of site preparation in order to house their colony. The behaviour of the ants was called "blind bulldozing" since they built their nest like little bulldozers and inhabited rock crevices where light could not reach [3]. Ants built their nests by plowing fill outwards from their nest site. An ant would continue to push until the force of the material back on the ant exceeded some threshold. The ant then would head off in a new direction to plow. This behaviour cleared an area large enough for the ant colony to inhabit.

There is much research going on in collective robotics outside of construction. Algorithms studied have included sorting [2], transport [5], [7] and foraging [6]. The general construction task could be viewed as the synthesis of foraging, transport and sorting. Building materials must be found (foraged), brought to an appropriate location (transported) and then assembled in an appropriate fashion (sorted). Thus collective construction builds on the work of [2], [5], [6], [7] and that of others who have worked in these fields. Some of these subtasks may be omitted or combined. In blind bulldozing, sorting is omitted as all of the material covering the future nest site is to be removed. Foraging and transportation are combined into a "plow outwards" task. To our knowledge, the system described in this paper represents the first time that a group of physical robots has cooperated to build a specific common structure.

The blind bulldozing approach uses stigmergy [2] to control the construction process. The work of each robot affects the other robots' behaviours via the modification of a shared environment. As material is pushed outwards, it packs together, creating walls of increasing strength. If we assume that the material to be plowed is spread uniformly about the construction site initially, the amount of material in a section of a nest's wall should be proportional to the distance that it has been pushed back from its initial position. Thus, the nest should stop growing as its walls eventually will thicken to the point where the robots can no longer move them.

B. Research at the University of Alberta

The blind bulldozing algorithm requires robots that can move on a flat surface with minimal sensing capabilities. Although the ants that our algorithm is based upon used several other construction techniques, we have focused on blind bulldozing because of its elegant simplicity. We are interested in the growth of the nest over time. We believe that a nest constructed via blind bulldozing will reach an equilibrium size determined largely by the properties of the material to be plowed.

Each of our robots only needs two sensors. One sensor measures the force exerted on the robot by the rocks that it is plowing and the other detects collisions with other robots in the nest. The blind bulldozer controller is implemented as a three state finite state machine, shown in Figure (1).

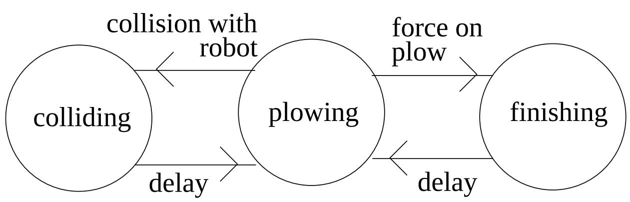

Fig. 1. The blind bulldozing algorithm can be implemented as a three state finite state machine. Robots spend most of their time in the plowing state, where they wander the nest and push any rubble ahead of them into the nest's walls. When the material that a robot is pushing exerts a force on it that exceeds a certain threshold, the robot reorients itself to a new heading and continues as before. A similar reorientation occurs if a robot experiences a collision with another robot. The delays on the transition back to the plowing state are incurred while the robot reorients.

Robots normally are in the *plowing* state. Here, a robot moves in a straight line, plowing up the material - gravel in our case - in its path. When the force of the gravel on a robot (due to friction) reaches a threshold, the robot switches to the *finishing* state. In this state, a robot turns a random amount and then reverts to the plowing state. While in the plowing state, if a robot detects a collision with another robot, it will switch to the *colliding* state. Here, as in the finishing state, a robot turns a random amount and then switches back to the plowing state. The key difference between the finishing and colliding states is that the finishing state is entered when a robot has done something productive since it has pushed back the nest wall some amount, contributing to the nest's construction. On the other hand, when a robot enters the colliding state, it has interfered with a nestmate. Robots interfering with each other must turn their attention away from nest construction and instead maneuver to avoid each other. The distinction between these states was made so that when we developed our model, we could use the robot states to indicate what is going on in the nest. That the reactions to the plow force exceeding its threshold or a collision are the same is coincidental. It is important to note that robots may not be plowing material at all times while in the plowing state. For example, robots that are crossing the nest are in the plowing state regardless as to whether they are pushing gravel or not.

In the next section, we present a mathematical model of the blind bulldozing algorithm. In Section III, we discuss the experiments that we carried out with robots in our laboratory. Section IV discusses our experimental results in comparison to the predictions made by our model. We close with a brief summary of our work and outline some of our future research goals.

II. A MATHEMATICAL MODEL OF NEST CONSTRUCTION

In this section, we present a method to model the behaviour of our multiple robot system in terms of how the nest grows over time. We proceed as follows. In Section II-A, we derive the equilibrium size of a nest built by blind bulldozing. In Section II-B, we examine the rate at which a nest being built by a solitary robot should grow and how this rate changes as the nest grows. Section II-C describes a probabilistic description of our system for any robot population. This description is based on a Markov chain representation of our system. Finally, in Section II-D, we combine Sections II-B and II-C in order to describe the growth of a multiple robot system's nest over time. For a description of the variables used in the following developments, refer to Table (I).

ρ_o	distribution of unplowed gravel
F_g	friction due to a single piece of gravel
F_{p_o}	force threshold of the robots' plows
$r_o > 0$	initial radius of the nest
$r_n \geq r_o$	current radius of the nest
w_r	width of the robots' plows
s_o	speed of the robots

TABLE I

THIS TABLE LISTS THE VARIABLES THAT WE USE IN OUR THEORETICAL ANALYSIS OF BLIND BULLDOZING.

A. On the Final Size of a Nest

In our system, each robot is capable of building an entire nest on its own. Also, the addition of robots to our system does not introduce new construction methods. That is, two robots cannot behave in a strictly cooperative [5] manner to accomplish some feat that a single robot could not have accomplished on its own. The final size of the nest depends only on the environment (the density of material to be moved and its friction with the working surface) and the strength with which robots push on the nest wall, F_{p_o}, which is constant throughout the construction process. This nest size can be derived as Equation (1).

$$r_{n_{equilibrium}} = \frac{F_{p_o} + \sqrt{F_{p_o}^2 + (F_g \rho_o w_r r_o)^2}}{F_g \rho_o w_r} \tag{1}$$

Equation (1) was found by calculating how much gravel would have to be incorporated into the nest walls to make them just strong enough to resist being moved by a robot. This amount of gravel is equivalent to the difference between the areas of the final and initial nests via the density with which gravel is spread about the working surface initially [8], ρ_o. Note that the robot population does not affect the final nest size.

B. The Growth of a Nest Containing One Robot

In a system containing just one robot, the robot criss crosses the nest along random straight lines. When the robot encounters the nest wall, it pushes against it with force F_{p_o} and then heads off along a new straight path. Refer to Figure (2). We make the assumption that at any time, the nest's walls are of uniform thickness. Therefore, regardless of where on the nest wall the robot pushes, the resulting increase in nest size will be the same. Further, if we assume that the nest is circular, then the robot wanders the nest along its chords. Since our robots tend to increase the size of their nest only a small amount on each push and because their pushes against the nest's wall are randomly distributed along the wall, the nest will tend to expand slowly, preserving its initial shape. If the nest starts out as a circle, it will tend to retain this shape as it grows.

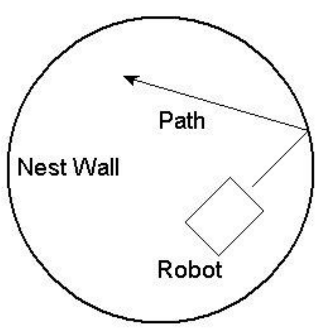

Fig. 2. A single robot constructing a nest. With no other robots in the nest to get in its way, a single robot wanders its nest along the nest's chords. At the end of each chord, the robot pushes against the nest wall, expanding the nest. After pushing against the nest wall, the robot reorients itself to a random heading and resumes straight line motion.

It only is when the robot reaches the end of each chord that the nest will expand some amount as this is where the robot will push against the nest wall. Thus a nest's growth is not continuous. Rather, it occurs in steps separated by the time that it takes a robot to traverse the chord of the nest ahead of it. It only is at the end of each growth step that the robot will switch to the finishing program state. Thus a robot switching to the finishing state signals a growth step in the nest's construction. Since the robot's orientation is random after reverting to the plowing state, the robot will, on average, traverse the mean chord of the nest between growth steps. The delay between growth steps is given in Equation (2) and is a function of the robot's speed and radius of the nest. Of course, after each growth step, the nest will have expanded, increasing the length of its mean chord.

$$t_1 = \frac{1.27 r_n}{s_o} \tag{2}$$

The new nest size after the next growth step takes the form of Equation (3). Note that Equation (3) holds regardless of the robot population. It does not matter whether one robot pushes against the nest wall twice or two robots push once each, the resulting nest growth will be the same.

$$r_{n_{new}} = \sqrt{r_{n_{old}}^2 - \frac{w_r}{2\pi} r_{n_{old}} + \frac{F_{p_o}}{\pi F_g \rho_o} + \frac{w_r r_o^2}{2\pi r_{n_{old}}}} \tag{3}$$

The growth of a nest containing one robot can be plotted in the following way.

- Calculate the time until the next growth step with Equation (2).
- Calculate the new nest size after the growth with Equation (3).
- Repeat to generate additional data points of the form (time, radius).

It is important to note that we are assuming deliberate construction only. *Accidental* construction, such as when a robot expands the nest during a reorientation, is ignored. Accidental construction will be revisted later in Section (IV).

C. Statistical Description of the General n-Robot System

A nest grows a small amount whenever a robot encounters the nest wall. In the case of a one-robot system, we calculated the mean path of the robot and thus the mean delay between the growth steps of a nest. With multiple robots, it is not so straight forward. Now, robots may reorient themselves anywhere in the nest due to collisions with their nestmates. In this section, we use a Markov chain to calculate the probability of a robot expanding the nest in an *n*-robot system.

At any given moment in an n-robot system, the n robots will be in one of their three program states. We use Lerman's description of the state of a multiple robot system [6]. Each system state will be denoted by an ordered triple, (x, y, z), where x, y and z are the numbers of robots in the plowing, finishing and colliding program states respectively.

A robot that changes program state changes the system's state. In order to keep the computational complexity of our model reasonable, we will allow only one robot to change state at a time.

The state diagram of a two-robot system is provided as an example in Figure (3).

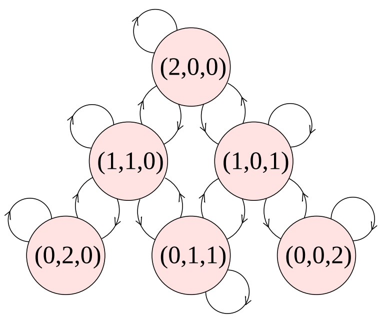

Fig. 3. The system state diagram of a two robot system. Each system state is denoted by an ordered triple, (x, y, z), where x, y and z are the numbers of robots in the plowing, finishing and colliding program states respectively. We allow only one robot to change state at a time to limit the number of possible state transitions from any system state to five or less. The state transition probabilities of this system are used to calculate the probability of a robot in the system contributing to the nest's construction.

We make the assumption that the robots' positions are random from one instance to the next[1]. A Markov chain is used to calculate two sets of probabilities. The first of these probabilities are the probabilities of finding the system in each of its states, $P(x,y,z)$, which are found as the stationary state of the Markov chain. The second set of probabilities are the probabilities of the number of robots in the finishing program state increasing from each system state. Probabilities in this second set are denoted as $P((x-1,y+1,z)|(x,y,z))$ and are a subset of the elements of the Markov chain's transition matrix. By multiplying and summing these probabilities as shown in Equation (4), we obtain the general probability that a robot will enter the finishing state of its program. The probability of a robot entering the finishing program state is the same as the probability of growth occurring in the nest.

$$P_n = \sum^{states} P(x,y,z) \times P((x-1,y+1,z)|(x,y,z)) \quad (4)$$

[1]This assumption effectively holds true, especially for larger system populations.

D. The Growth of Nest Containing n-Robots

We now will develop an algorithm to predict the growth of the nest of an n-robot system. We begin with a final assumption. Consider two events, A and B, with the probability of occurring P_A and P_B. We make the approximation that if A occurs, on average, every t_A seconds, then t_B can be approximated by Equation (5).

$$t_B = \frac{P_A}{P_B} \times t_A \quad (5)$$

We have t_1, the time for progress to occur in a one-robot system, from Equation (2). We can also calculate the probabilities of incremental progress occurring in both an n-robot system and a one-robot system (P_n and P_1) with Equation (4). Thus we can easily calculate t_n, the time for progress to occur in an n-robot system, as shown in Equation (6).

$$t_n = \frac{P_1}{P_n} \times t_1 \quad (6)$$

One can predict the growth of an n-robot system's nest as follows:

- Calculate t_1 using Equation (2).
- Calculate P_n and P_1 using Equation (4).
- Calculate t_n using Equation (6).
- Calculate $r_{n_{new}}$ using Equation (3).
- Repeat as necessary, as in Section (II-B).

Again, as in Section (II-B), we are assuming that only deliberate construction occurs.

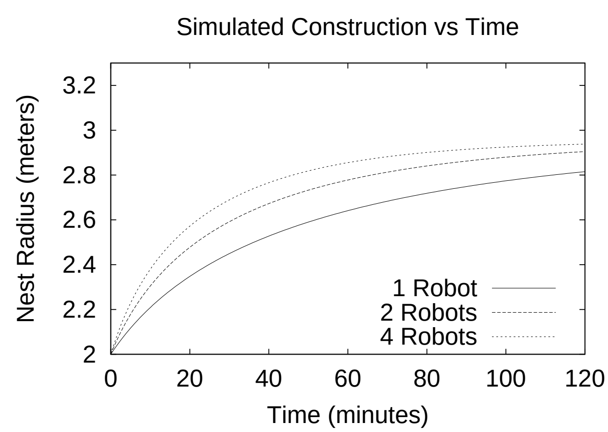

Fig. 4. A graph of simulated nest construction for the three robot populations used in our actual experiments. The nest grows quickly at first because its walls are thin and easy to push back. As the nest grows, its walls thicken causing its growth to slow. Eventually, the nest will reach a final equilibrium size where its walls are too thick to push back any further.

Using this modeling strategy, we can calculate the rate of growth of a nest for various robot populations. See Figure (4) for the growth of a typical nest for robot populations of one, two and four.

III. Nest Construction by Real Robots

Our experiments were carried out on a large flat surface using one to four robot bulldozers and landscaping gravel as a building material. Each bulldozer was outfitted with a force sensitive plow and a collision sensor.

Our hypothesis is that an increase in population size should increase the rate of nest construction, but not the final nest size. Nest construction experiments were carried out with one, two and four robots to test this theory.

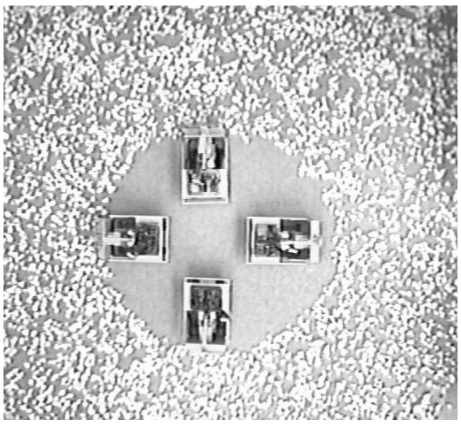

Fig. 5. The initial state of a four robot experiment. Landscaping gravel is spread evenly over a large square region with a clear circle of radius 0.6m in its center. The robots are placed in the clearing. The robots employ the blind bulldozing strategy for two hours to build their nest while being recorded by an overhead camera.

A square area, approximately 2.5m × 2.5m, on the floor of our lab was marked off with tape (no walls were present). In the center of this square, we drew a circle of radius 0.6m with a pencil. Landscaping gravel was spread uniformly over the region inside of the square but outside of the circle. The circle served as an initial nest for our robots. However many robots were to take part in a particular experiment were placed in the center of the circular clearing, facing outwards. Our robots travel at 20cm/s and have plows 20cm wide. A picture of the starting state of our system can be seen in Figure (5).

The robots carried out blind bulldozing for two hours and were recorded on video tape using an overhead camera. The video data was analyzed by measuring the area that had been cleared. The nest radii were plotted vs time to view the rate of growth of the nests. Refer to Figure (6) for a graph of our experimental results[2].

IV. Discussion

We have demonstrated the viability of our blind bulldozing algorithm for a group of decentralized robots. Our attempts to model the behaviour of our robots led us to what we feel is a novel approach to multiple robot system modeling. What are the key aspects of the behaviour of our system and how does our model capture them?

All of our experiments showed the same general behaviour: quick initial growth which slowed as a nest enlarged. This makes good sense. Initially, a nest's walls are thin and easy to push back. The robots, which always pushed with the same force, were able to move the walls back less and less as they thickened. This behaviour was predicted by our model. The initial shape of the nest was preserved, too. Because the robots pushed the walls back only a little at a time and because their pushes tended to be equally distributed over the entire length of the nest wall due to the randomness of the robots' reorientations, the initial nest shape simply swelled outward. Examine Figure (7). This figure shows the final state of three of our experiments. Here, we can see that both the circular nest assumption and the assumption that the nest wall would be of uniform thickness are well satisfied.

[2]The scales on Figures (6) and (4) are different. This is because we calculated P_n for our model using geometric approximations that became inaccurate for nest radii below 2m, while starting radii of approximately 0.6m were the largest that we could accommodate in our lab.

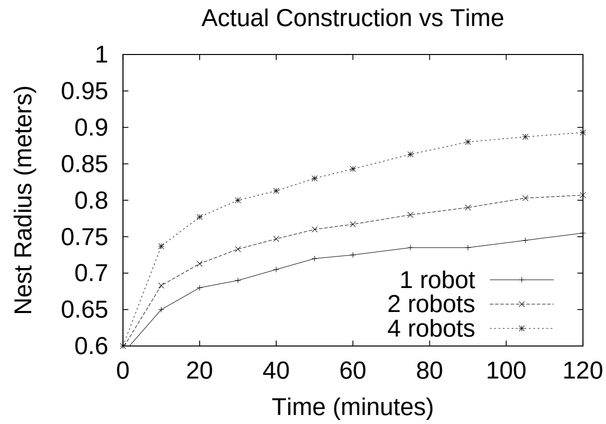

Fig. 6. Nest construction by real robots. This graph shows the average radii of the nests being built by one, two and four robots vs time. Note the similarity to the predictions that our model made about this system in Figure (4). The growth of a nest is rapid initially because the nest's walls are thin. As the nest grows, its walls thicken and the rate of growth slows.

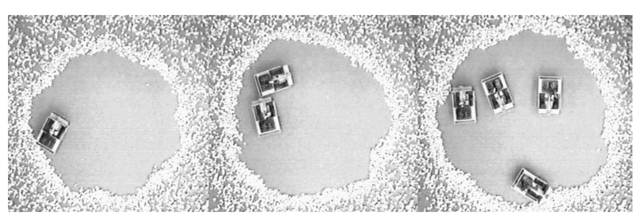

Fig. 7. Nests constructed by one, two and four robots after two hours. The nest retained its initial circular shape and has uniform walls because the blind bulldozers enlarge the nest by distributing their pushes against the nest wall along its entire length.

We can see that as time passes, the efficiency of the construction process decreases. More energy is expended by robots as they wander a larger nest, while they push the nest's walls back less and less.

In Sections (II-B) and (II-D), we made a distinction between deliberate and accidental construction. Deliberate construction occurs when a robot pushes against the nest wall with its plow. Here, a robot reorients itself after the force of its pushing exceeds is plow threshold, F_{p_o}. Accidental construction occurs whenever robots pushed back the nest wall with something other than their plows. This operation takes place when robots back into the wall or rotate too close to it. Accidental construction is not force limited like deliberate construction and therefore is uncontrolled. Accidental construction is a symptom of inter-robot interference, usually appearing in conjuction with robot to robot collisions. Many multiple robot systems that have been studied exhibit a performance peak at some particular system population [5]. In our system, the side effects of overpopulation are similar to those of the specified system task (expand the nest). The distinction, then, is in the level of control. In Section (II-A), we showed that the final nest size of our system should not be affected by the population of the robot swarm that constructs it. For us, how close a final nest size is relative to how large it should be is a measure of system performance. The four robot nest appeared to grow faster than it should have. The increase in the speed of construction due to a larger number of robots came at cost of decreased accuracy in the final product. We suspect that additional robots would further increase the rate of nest construction and further decrease the control that we have over the final nest's size.

Regarding nests reaching equilbrium, rough calculations suggest that a one robot system would take upwards of 16 hours to finish construction. Most of the clearing is completed in the first two hours. The ants that inspired our work would not work on their nests indefinately. They have other concerns, such as foraging for food and caring for their brood. Once their nest had stabilized, they likely would turn their attention elsewhere. By measuring the length of time between nest wall pushes, our robots could estimate their nest's size and its rate of growth. Once the nest growth slows below some rate, the robots could turn their attention elsewhere, too. For example, the robots could start to erect a structure on the foundation that they had just cleared.

V. Summary

In this paper, a robust algorithm for collective robotic construction was presented. Our robots used a technique known as blind bulldozing to create clear regions in a field of gravel. Blind bulldozing first was observed as a subset of the construction behaviours of a species of ant. Because of the minimal sensory and mechanical constraints imposed by the algorithm, blind bulldozing would be suitable for applications where the cost, complexity and reliability of the participant robots is an issue. We have described a technique with which to establish a theoretical model for the collective construction task. The theoretical model is verified with physical experiments involving one to four robots. Good agreement between the theoretical prediction and experimental data has been obtained.

Our future work will look at how to augment blind bulldozing. We currently are investigating ways to modify our robots' controllers in order to specify features of the final nest, such as shape and size. We will also examine the possibility of applying our Markov modeling technique to the analysis of other collective tasks, in order to study the general properties of these systems.

VI. Acknowledgments

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