Using Templates for Defensive Wall Building with Autonomous Mobile Ant-Like Robots

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Abstract. This paper reports on the preliminary findings of the application of collective minimalist robotics to the task of wall building. In particular it shows how linear wall structures, composed of circular objects, can be formed by a group of simple mobile robots without recourse to direct communication, sophisticated sensing or intensive computation. Studies on social insects, such as ants, reveal that construction of complex nest structures are built by animals with no internal 'blue-print' of the global structure. Such structures emerge as the consequence of the interactions of the insects, carrying out simple behaviours, and the environment. In particular, the exploitation of heterogeneities, referred to as templates, is investigated. Such a biological paradigm involving simple 'agents' limited in their capacity for computation, communication and sensing has an obvious appeal to those researching into minimalist collective robotics. The underpinning biological mechanisms may be of particular importance when building very small robots where computation, sensing and ability to communicate may be seriously constrained.

1. Introduction

It has been argued that engineers like to make systems with certain characteristics including: [1] use of simple components, [2] use of many identical modules, [3] reliability of system operation, [4] adaptability to environmental changes and [5] robustness with respect to component failures [Holland & Melhuish 1996]. Social insects, such as ants, arguably provide an existence proof of minimalist collective control mechanisms which employ decentralized control, self-organization, redundancy and stigmergy which is a form of indirect communication through the environment [Melhuish *et al* 1998]. Studies on social insects, such as ants, reveal that construction of complex nest structures are built by animals with no internal 'blue-print' of the global structure. Such structures emerge as the consequence of the interactions of the insects, carrying out simple behaviours, and the environment. Such techniques may well be useful to those engaged in building micro-robots where small dimensions impose limitatations on sensing, computation, communication and power.

This paper develops the idea that these minimalist collective characteristics could be interesting to engineers engaged in designing and building multiple robot systems. Inspired by nest construction behaviour in ants [Franks & Deneubourg 1997] this study explores simple wall building by a group of many simple robots. In particular, attention is focused on the use of environmental heterogeneities or discontinuities, referred to as templates, in the environment. For this study no robot holds an internal representation of the task in terms of a world model [Brooks 1991]. The task is achieved as the emergent consequence of the robots executing simple reactive rules triggered by local conditions.

The paper is organised as follows. Section 2 introduces the nature of environmental templates and how they might be used by natural collective systems such as ants in wall building. Section 3 describes the material and methods used for the experiment discussed in section 4. The results presented in section 4 are discussed in section 5.

2. Background and Motivation

2.1 Templates

The motivation for the study comes from observations of wall building in natural social insect systems and the exploitation of heterogeneities or 'templates' in the environment. Many ant species such as *Myrmica*

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rubra [Thome 1972] make use of temperature and humidity gradients when building nests and distributing their eggs, larvae and pupae. Theralauz *et al* [1998] state that the behaviour of most insects is influenced by heterogeneities in the environment. They define a template as a heterogeneity which is a perceptible (by the insects) deviation from a uniform distribution or constant quantity. Thus predictably varying quantities such as varying light levels, chemical concentration gradients and soil levels can be included. Thus the insects' behavioural repertoire of simple probabilistic stimulus response behaviour can be influenced by such templates. Theralauz *et al* [1998] state that insects tend to walk, build, store or lay eggs along such heterogeneities. Templates may either be natural phenomena or directly provided by the insects themselves. A classic example of an insect generated template is in the construction of the queen's royal chamber in a termite nest [Bonabeau *et al* 1997, Bruinsma 1979]. In brief, the building of the walls of the queen's chamber are sited in a location which is a function of the queens body shape and in the case of *Macrotermes subhyalinus* a pheromonal template in the form of a decreasing gradient around her. Experiments have shown that a key factor is that workers deposit a soil pellet if the pheromone concentration lies within an upper and lower concentration window.

For completeness it is worthwhile putting the use of such templates into context. Social insects employ self-organization in many of their collective activities [Bonabeau *et al* 1997]. Self-organization derives its origins from physics and chemistry in an attempt to describe how microscopic processes could give rise to macroscopic structures in systems which are not in equilibrium. [Nicolis & Prigogine 1977]. Self-organization, according to Theralauz *et al* [1998] is considered as a set of dynamical mechanisms whereby structures emerge at the global level of interactions among the lower level components. A key concept is that the rules which specify the interactions among the system's component elements are executed on the basis of purely local information. Some researchers such as Bonabeau *et al* [1997] suggest that self-organization is not a universal mechanism, in that it does not by itself account for all social insect activity. In particular, according to Bonabeau *et al* self-organization is combined with the mechanism of stigmergy. Stigmergy is a form of indirect communication mediated through the environment [Grasse 1959, Melhuish *et al* 1998]. Another possibility is the exploitation of heterogeneities which already exist in the environment. These heterogeneities are referred to as templates. This paper focuses on the combination of a simple rule repertoire and environmental templates to achieve wall formation among a group of minimalist mobile robots.

2.2 Wall Building

In particular, it has been observed by Franks & Deneubourg [1997] that *Leptothorax tuberointerruptus* ants build a dense circular wall from sieved sand around a central cluster of brood. It appears that ants carrying building particles make contact with the brood cluster which triggers the deposition of the 'brick' at a particular distance from the brood cluster. Sendova-Franks [personal communication 1999] has observed the construction of a defensive linear wall formation in the same species. A *Leptothorax tuberointerruptus* ant colony creates a nest in a rock crevice. Observation of *Leptothorax tuberointerruptus* shows that firstly, brood is brought into the nest and deposited and clustered toward the end of the nest furthest from the entrance. After this phase a defense wall of sand grains is then created across the nest entrance. Creating a nest between two glass slides with three walls and one open side Sendova-Franks has observed and recorded the brood and wall building behaviour of the ants. Figure 1 illustrates the configuration of brood and sand clusters after many hours of work by the ants in a glass slide nest. It is not proven but extremely likely that the ants are using some environmental information relating to the entrance position to assist in their orientation. Templates or environmental heterogeneities composed of light gradient fields, humidity, pheromone or some combination may be employed.

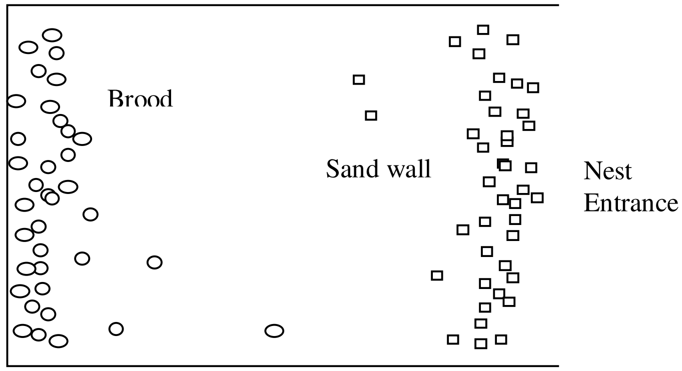


Figure 1. Leptothorax nest with defensive wall

3. Materials and Methods

The robots and experimental environment used in this study were designed to investigate a range of social insect behaviour, with particular emphasis being placed on building tasks. The design of the robot system was inspired by the work of Deneubourg *et al* [1990] on corpse clustering in the ant *Pheidole pallidula* and Franks and his collaborators on ant species *Leptothorax tubero-interruptus, Leptothorax unifasciatus,* and related species [Franks and Sendova-Franks 1992, Franks *et al* 1992]. These ants live in small colonies (typically with a few hundred members) in cracks in rock. This constrained environment means that they are behaviourally adapted to life in two dimensions. It is therefore possible to study the behaviour of a colony by providing it with a particular two dimensional habitat - the space between two glass slides - which allows unrivalled opportunities for observation and recording.

For collective minimalist robot investigations *Leptothorax* is also particularly interesting, because our current robots, which are wheeled, operate well in two dimensions but are extremely limited in their abilities to operate in the third dimension. *Leptothorax* building behaviours tend to involve the movement of single lumps of material (carborundum grit of regular dimensions is usually provided by the experimenters) which are placed next to other lumps rather than piled on top of them. A similar level of functionality can be achieved in robots by simply pushing and pulling building blocks or pucks (actually frisbees) around the floor, rather than lifting them and piling them up. The comparative dimensions a puck and robot are similar to those of a sand grain and *Leptothorax tuberointerruptus* ant.

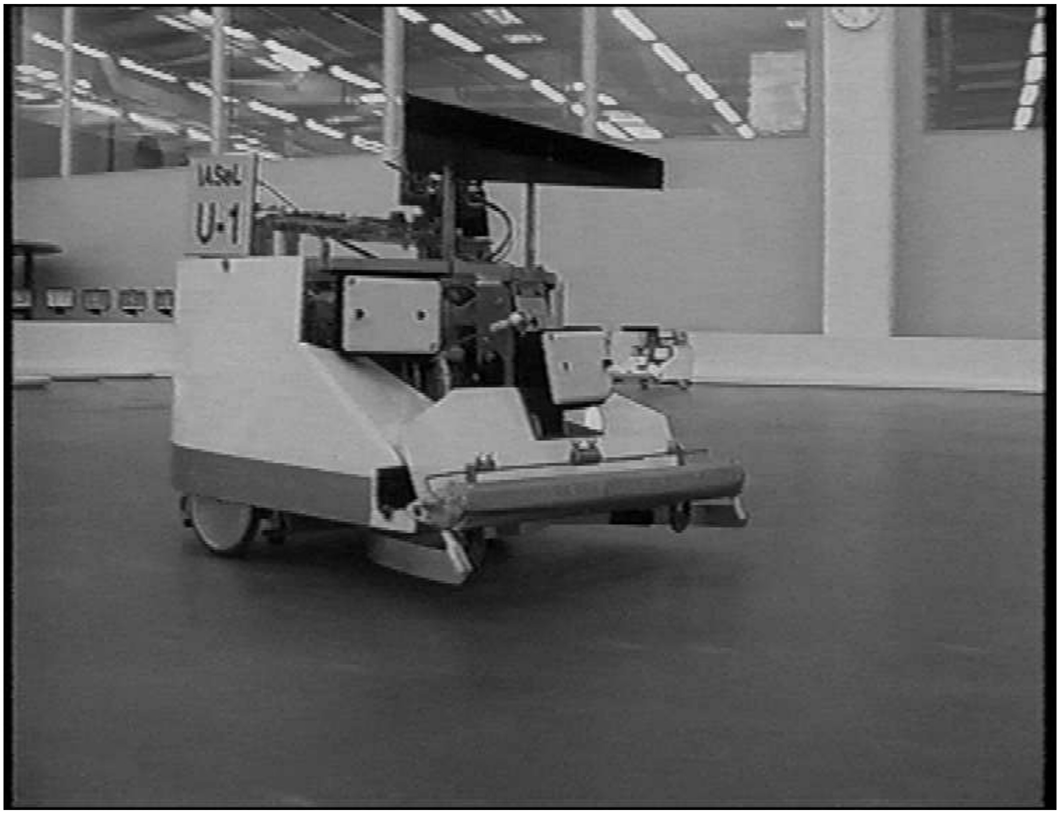


Figure 2: A U-bot

The robots, known as u-bots, (see Figure 2) were designed and built in our laboratory to provide a flexible and capable platform for a range of collective robot experiments. The design and operation of the robots is described in detail in Melhuish *et al* [1998]. Each robot can detect obstacles (walls and other robots) and has a scoop mechanism attached to a microswitch which is adjusted such that it is not triggered when the gripper strikes or pushes a single frisbee, but is always triggered by two or more. Figure 3 shows three u-bots involved in creating puck clusters.

The robots are run in a large arena which is octagonal in shape, with 1.75 metre sides and over 9m across; the area is 1760 times the area of a robot. (This is the same order of magnitude as the ratio of the area of a *Leptothorax* nest to a single ant.) A video camera mounted 6 metres above the centre of the arena is linked to a PC based video capture system which automatically records an image at preset intervals. The intention is that eventually the images will be automatically processed by an image analysis system to yield the coordinates of pucks of each colour. However, the distortion produced by the lens means that a calibration and preprocessing stage must first be undertaken, and this has not yet been completed. The images reproduced in this paper show this distortion, which over-emphasises the central area of the arena, and care must be exercised in their interpretation. 93 pucks were placed in the arena with a uniform and regular spacing, and 6 robots were released. The overhead video system was set to record a frame every 5 minutes. When a robot stopped due to battery failure it was removed and the battery was replaced. The program was reloaded and it was then placed back in arena. A battery change took approximately 3 minutes.

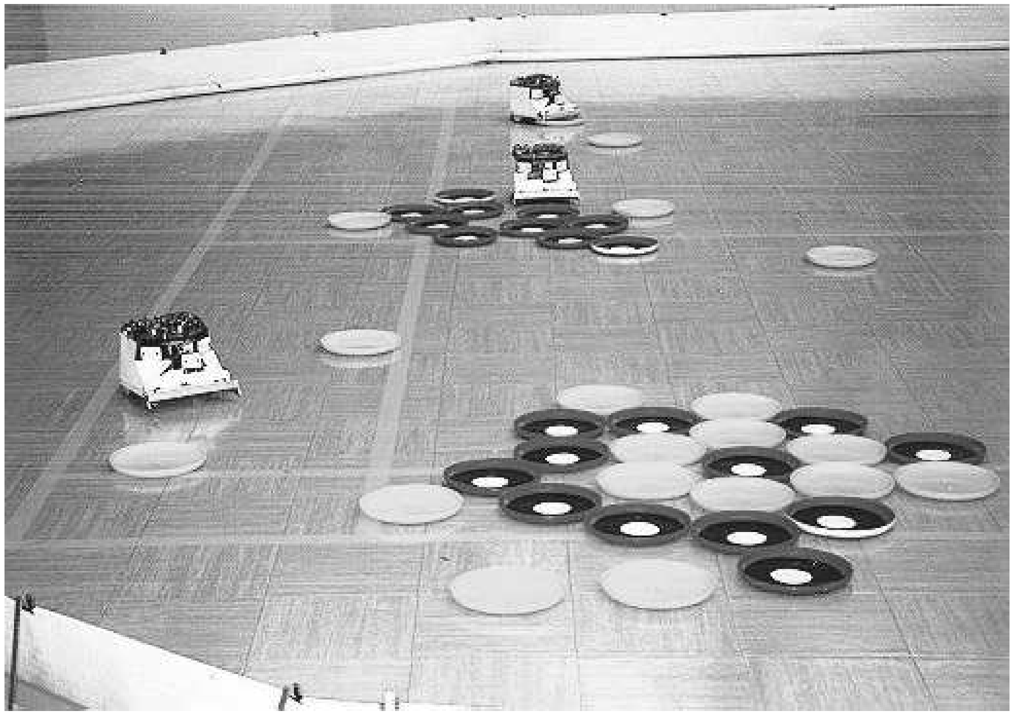


Figure 3: cluster building with U-bots

4. Experiment and Results

An experiment was conducted to investigate the possibility of building a linear wall structure across the robot arena. From *Leptothorax* building studies it is speculated that ants might employ two templates in the creation of linear wall structures. The entrance of the nest may represent some gradient discontinuity or heterogeneity such an O_2 concentration. It is also possible that the presence of the brood could create a further CO_2 gradient. Two templates were therefore employed in the robot wall building experiments. The first was a strip of white tape across the arena which represented the nest entrance (see Figure 8a). The tape could be detected by an opto-sensor positioned under the robot when it moved across the white line. The second template consisted of a bank of halogen lights at the ‘west’ side of the arena (see Figure 8a). The lights provided a gradient field across the arena. For each trial 93 pucks were set out in a regular pattern (see Figure 8a).

Each robot was programmed with the simple reactive rule set set out below. Three trials with 6 robots were conducted each lasting 150 minutes. The last trial was extended for a further 90 minutes to observe stability of the final structure. For each trial the success of wall construction was measured in terms of the percentage of the arena diameter covered by pucks, the percentage of pucks which lie within 1 metre of the ‘demanded’ wall site (i.e. a line 1.5m from the white line template) and the mean distance of pucks from the wall site.

```
Rule 1:
if (scoop pressed and Object ahead) then /*i.e. hit wall or robot*/
    make random turn away from object
endif

Rule 2:
if (white line detected and a puck is in scoop) then
    turn towards light
    move forward 1.5m

    /*check to see if robot has not moved through1.5m */
    if (scoop depressed before completing distance) then
        retain puck and make 180⁰ turn
    else
        Drop puck (by reversing)
        make 180⁰ turn away
    endif
endif

Rule 3:
if (while moving the robot picks up a puck) then
    turn away from light
endif

Rule 4:
if (scoop pressed and no object ahead) then /*hit at least another puck
    make 180⁰ turn away
endif

Rule 5:
go forward
```

Figure 5 simple rule set

4.1 Results

Figure 6 shows how the percentage of the desired wall length develops over the 150 minute period for each of the three trials. The graphs illustrate that in all three trials some 70% of the wall is rapidly completed in the first 15 minutes of each trial. In trials 1 and 3 the percentage of wall length remains quite stable. Trial 2 shows a distinctive reduction to 44% at the 90 minute mark which was due to a robot pushing through the wall. After this incident the wall was 'repaired' and trial 2 then recovered to 87% after 105 minutes. A similar story is reflected in Figure 7 which displays the percentage of pucks within 1m of the 'demand' wall site(1.5m 'left' of the white line template – see Figure 8a). For all three trials the percentage of pucks within 1m of the target line rapidly increase to around 60% in the first 30 minutes of each trial. For the remaining time the general trend is for the percentage of pucks to increase to around 80%. For each trial the end configuration, after 150 minutes, is shown in Figure 8b, c and d respectively. Figure 7 reflects the state of the wall in terms of the mean distance of the pucks from the target line expressed in puck diameters (23cm). For the three trials the mean distances were 3.83 (σ 4.13), 3.52 (σ 3.49) and 3.73(σ 4.07) puck diameters for trials 1,2 and 3 respectively.

Trial 3 was allowed to continue for a further 90 minutes to observe the stability of the solution. Figures 9 and 10 show that the percentage of wall built and the percentage of pucks within 1m of the target line continues to be essentially stable for the extended time.

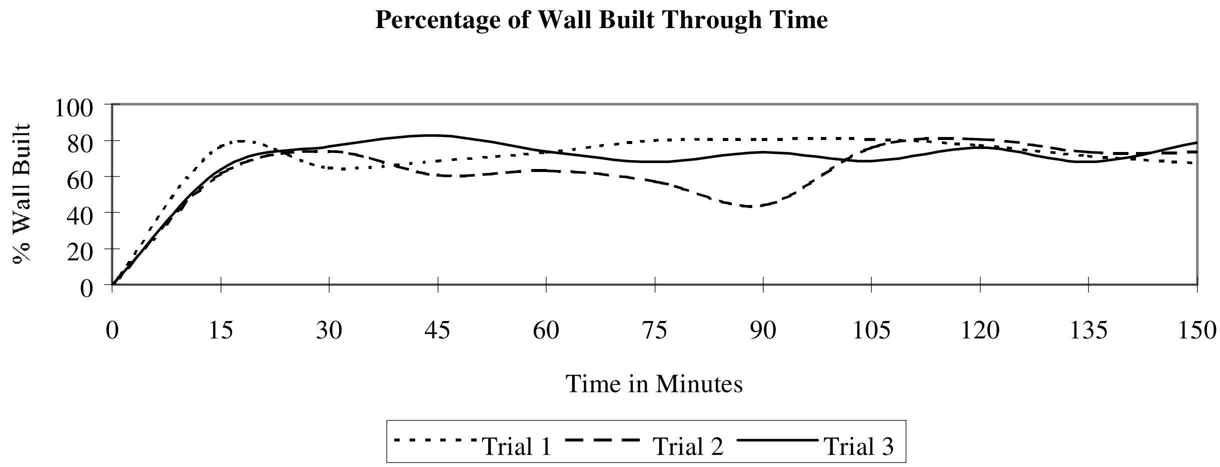


Figure 6 percentage of wall built during trials

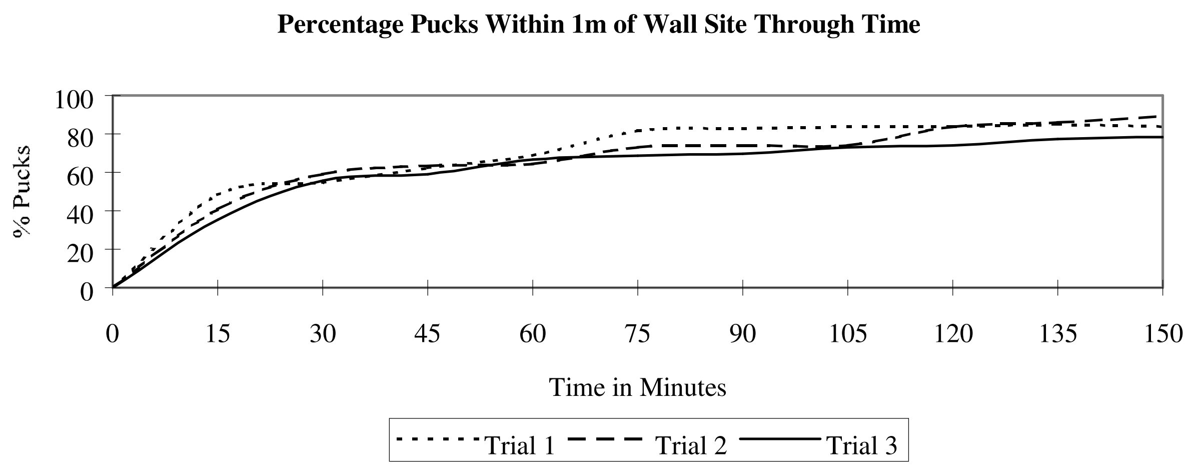


Figure 7 percentage of pucks dropped within 1 m of target line during trials

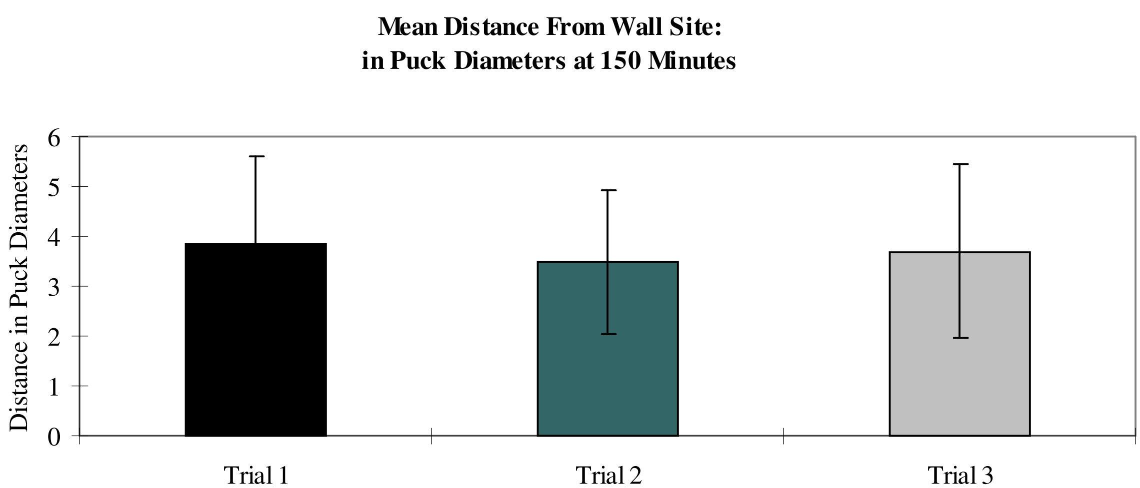
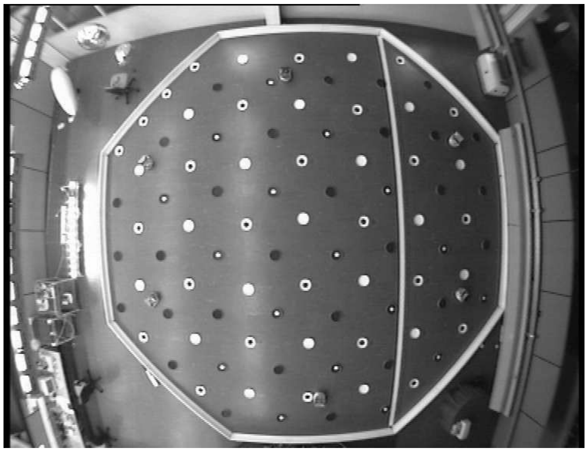
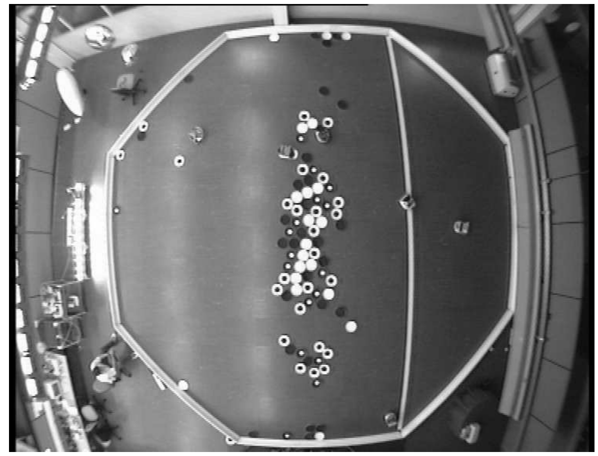


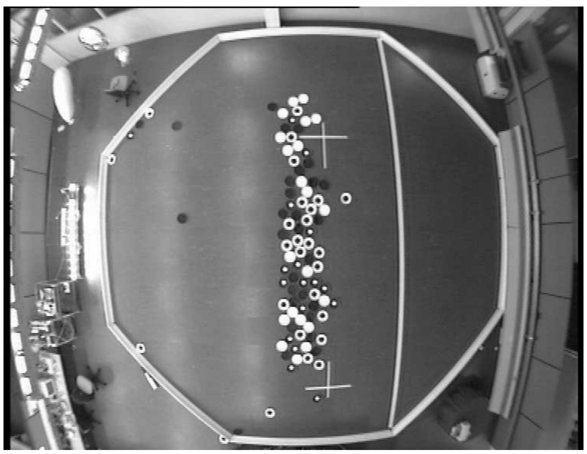
Figure 7 mean distance from target line

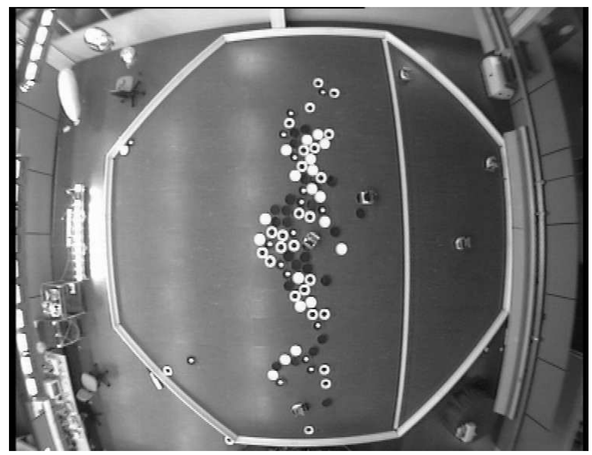




(a) start configuration

(b) end state for trial 1





(c) end state for trial 2

(d) end state for trial 3

Figure 8 start and end configurations

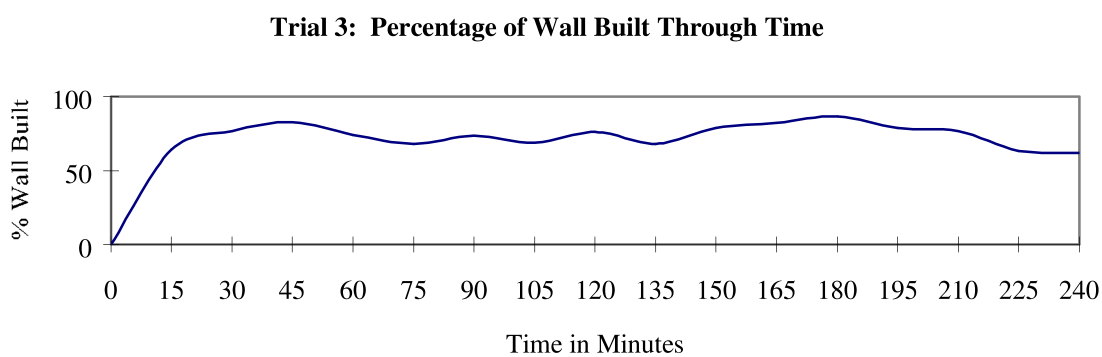


Figure 9 extended trial percentage of wall built

Trial 3: Percentage Pucks Within 1m of Wall Site Through Time

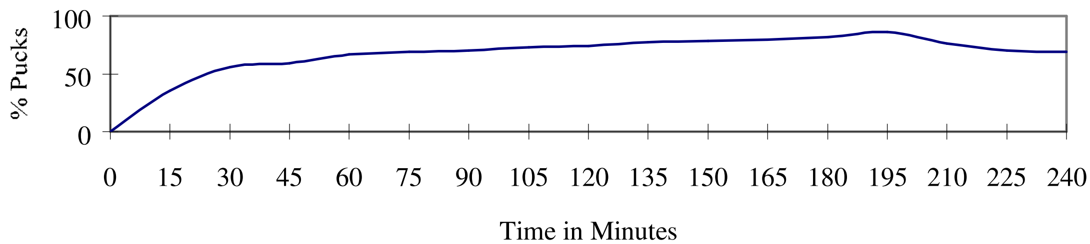


Figure 10 extended trial percentage pucks within 1m of target line

4.2 Conclusion

These preliminary results indicate that it is possible to create linear structures parallel to a discontinuity in the environment. In terms of the metrics applied, building rate is highest at the beginning of a trial and then tails off for the remainder of the building period. Extending the period of the trial (for one trial) indicates that the solution is stable. Wall building performance may be improved if the bank of halogen lights is lengthened. For these trials the length of the halogen light array is considerably shorter than the diameter of the arena. Since the robots are required to make an imprecise turn toward the light, robots making such a turn near the end of the template, that is near the arena boundary, will in general not make a turn perpendicular to the template. They will make a turn biased toward the centre of the arena. Thus pucks will tend not to be deposited near the arena boundary. This effect is observed in the trials. Figure FF b, c and d illustrate the effect where the wall building is concentrated toward the centre, leaving gaps at the ends of the structure.

5. Discussion

It has been argued that social insects, such as ants, provide an existence proof of minimalist collective control mechanisms. It is possible that certain application domains may benefit from the employment of multiple mobile minimalist machines. This paper, inspired by an example of wall building in a natural collective system, has focused on the aspect of exploiting templates to build linear wall structures. The robots are simple reactive mobile machines with rudimentary sensing and capable of (in the context of this experiment) making imprecise movement. These robots were given a simple rule set which when combined with two templates could create linear wall structures.

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