Multi-modal Swarm Construction

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Abstract

Swarm construction involves a population of autonomous agents collaboratively organising material into useful persistent structures without recourse to central co-ordination or control. This approach to fabrication has significant potential within nanoscale domains, where explicit centralised control of building activity is prohibitive (e.g., Martel and Mohammadi, 2010). The ultimate value of swarm construction will be demonstrated in the real world with physical agents (or perhaps software agents working with real-world digital media). However, our interest is in exploring different possibilities for decentralised control of swarm construction in abstract simulated environments populated by idealised simplistic agents. The goal of such simulations is not to demonstrate solutions to specific realistic construction challenges, but to capture elements of the fundamental logic of decentralised control.

Here, we explore a population of simple simulated agents that combine information from two sensory modalities (one proximal and one distal) in order to overcome some of the limitations of two previously explored uni-modal schemes. Like the artificial paper wasps of Bonabeau et al. (2000), the agents simulated here are able to sense the configuration of building material in their immediate environment and use this proximal sensory information to trigger specific building activity via a set of *microrules*. In addition, like the simulated termites of Ladley and Bullock (2004, 2005), they are also able to sense simulated diffusing artificial pheromones deposited during building and movement, and use this distal sensory information to influence movement and release or inhibit building activity. Since both the proximal configuration of building material and the distal distribution of pheromone intensities in an agent's vicinity are themselves the consequence of prior agent building activity, the scheme is *stigmergic*—the environmental trace of agent activity guides subsequent agent behaviour.

Movement and building activity are constrained by a simple physics such that agents cannot pass through building material and must remain in contact with the ground or built structure. Moreover, new building material may only be deposited in locations with sufficient support. In contrast to Grushin and Reggia (2006), these constraints, while simplistic, do *not* prevent concave, hollow or over-hanging structures.

In principle, this swarm construction scheme is "universal" in that it is capable (given enough distinct types of building material) of generating *any* configuration of contiguous building material—a property inherited from Bonabeau et al. (2000)'s scheme. However, proofs of universality tell us nothing about what a scheme will in fact be useful for in practice (Bullock, 2006). Consequently, we concentrate here on exploring and describing the scheme's *generic* behaviour: what classes of structure are readily built and why; conversely, what kinds of structure require a prohibitively complex set of building materials, pheromones, microrules, etc.

Here, using hand-designed agents we are able to show that, unlike Ladley and Bullock's (2004, 2005) termites, the addition of proximal microrules enables agents to construct both simple conic *and* rectilinear structures such as domes, arches, pillars, cubes and frames (see figure 1 for examples of the latter), and that they are able to combine these structures relatively easily (see figure 2). Moreover, we are also able to show that, unlike Bonabeau et al's (2000) wasps, the addition of distal pheromone-mediated behaviour enables agents to construct architectures exhibiting long-range structure without recourse to a prohibitive number of block types (as required by, e.g., Howsman et al., 2004), and that these structures can be easily scaled in size through manipulation of pheromone parameters. However, complex structures still present challenges in terms of managing interactions between agents obeying different rule-sets, and timing issues related to the establishment of pheromone templates before the initiation of pheromone-template-mediated building activity.

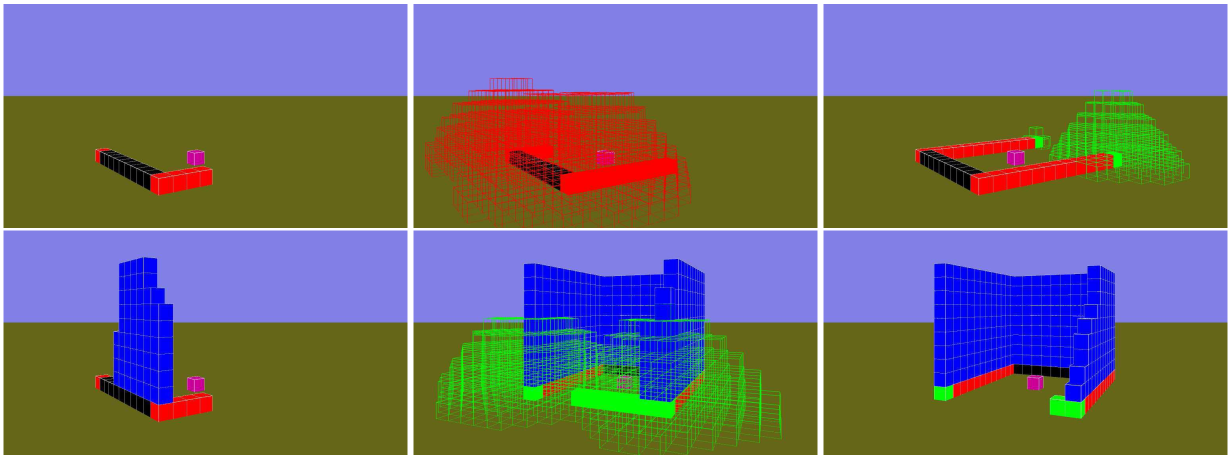

Figure 1: Stages in the formation of a square frame (top row), and a hollow cube (bottom row). In both cases building is initiated by the placement of a single block (depicted in magenta) in the centre of the ground plane. Distinct types of building material are represeted by solid cubes of different colours. Distributions of distinct types of pheromone are indicated by wire-frame cubes of different colours. Builder agents are not depicted.

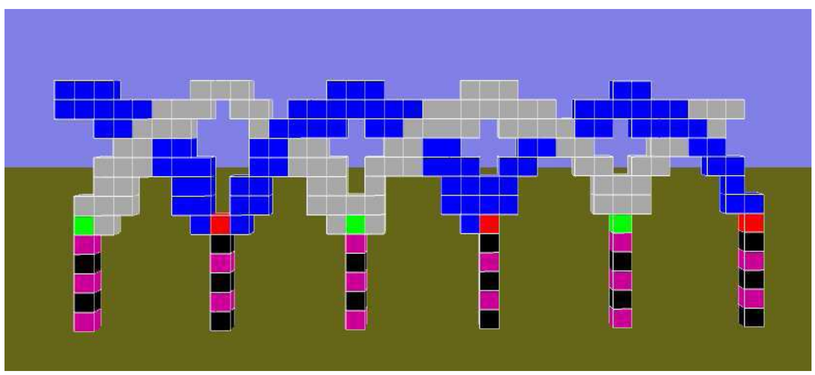

Figure 2: A series of interleaving arches mounted on a row of columns.

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