A Stigmergic Cooperative Multi-Robot Control Architecture

Thomas G. Howsman[1], Daniel O'Neil[2], Michael A. Craft[1]

[1]Dynamic Concepts, Inc.
P.O. Box 97, Madison, AL 35758
(thowsman@dynamic-concepts.com)

[2]NASA/MSFC, Marshall Space Flight Center, AL 35812
(dan.oneil@msfc.nasa.gov)

Abstract

In nature, there are numerous examples of complex architectures constructed by relatively simple insects, such as termites and wasps, which cooperatively assemble their nests. A prototype cooperative multi-robot control architecture which may be suitable for the eventual construction of large space structures has been developed which emulates this biological model. Actions of each of the autonomous robotic construction agents are only indirectly coordinated, thus mimicking the distributed construction processes of various social insects. The robotic construction agents perform their primary duties *stigmergically*, i.e., without direct inter-agent communication and without a preprogrammed global blueprint of the final design. Communication and coordination between individual agents occurs indirectly through the sensed modifications that each agent makes to the structure. The global stigmergic building algorithm prototyped during the initial research assumes that the robotic builders only perceive the current state of the structure under construction. Simulation studies have established that an idealized form of the proposed architecture was indeed capable of producing representative large space structures with autonomous robots. This paper will explore the construction simulations in order to illustrate the multi-robot control architecture.

Introduction

NASA's long term goals include construction of large space structures (Figure 1) which will require the assembly of structural elements numbering in the thousands, and will potentially be performed primarily by robotic means. Advantages of using robotic agents rather than astronauts for the assembly process include astronaut safety, construction efficiency, and cost savings. Comparisons between robotic assembly and human construction (via EVA) of structures have been made (Lake 2001), with conclusions stating that for very large structures (greater that 100m in dimension) some form of robotic assembly is required.

Although the need for robotic assembly in space has been established, many aspects of the required systems have yet to be developed. The research discussed herein focuses upon the overall assembly strategy from a distributed control point of view (Mataric 1995). In other words, how can the efforts of multiple robotic construction agents be coordinated so that the desired structure emerges from the assembly effort? Taking a cue from social insect behavior (Theraulaz *et.al.* 1995), a form of decentralized coordination based upon stigmergic principles appears promising. In this scenario, each individual agent's behavior is controlled by stimuli provided by the common environment of the emerging structure–a form of indirect communication. Rather than using direct communication between agents, each individual communicates with its fellow agents via the small changes each one makes to the structure under construction. In fact, the emerging structure itself serves as a form of external memory (Beckers *et.al.* 1994).

An advantage of stigmergic cooperative behavior is that massive redundancy is automatically built in to the system. Failure of a particular individual building agent (robot) will only slow the building process, not stop it. The required computer processing power of the individual agents is reduced by the fact that the overall design is not maintained, or even understood, by the agents (Valckenairs *et. al.* 2001). Rather, the final design is an emergent property of the stigmergic assembly algorithm. An individual agent in the system transitions from one state (e.g., platform assembly) to another (e.g., antenna building) based upon sensor inputs which monitor the local environment, or structure.

The initial phase of the research focused on the formulation of stigmergic building algorithms suitable for the assembly of large space structures. A software simulation of the cooperative building process was developed, allowing for visualization of the assembly process. An internet enabled version of the design and simulation tools is also available. Hardware demonstrations of the developed algorithms are currently underway using relatively standard robotic hardware.

Building Algorithm

During the assembly process, each individual assembly robot moves about the work volume by making discrete, but continuous, transitions from one cell to another. From the robotic agent's point of view, each

Figure 1. Future Large Space Structure. (SSI Image.)

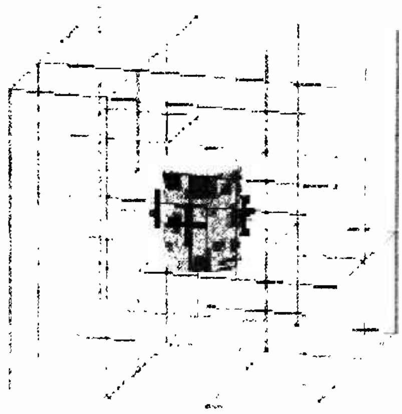


Figure 2. Cubic Sensor Lattice.

agent is centered in a 3×3×3 lattice of cubic cells, as illustrated in Figure 2. The agent occupies the center cell of the 27 cells in the lattice, and can move to any of the 26 neighboring cells that are unoccupied. An alternate hexagonal description of the work volume is also available for used by the algorithm.

The construction agent is assumed to possess sensors capable of detecting the presence of building objects or other robotic agents within the local 3×3×3 lattice. For the purposes of this research, we allowed for twenty distinct types of building blocks. It is assumed the agent can distinguish between the different colored blocks (blue, green, etc.) as well as other building agents which might be present within his sensor lattice.

The data visualization and rule building process is much easier if we utilize a two dimensional display map of the three dimensional sensor lattice (Theraulaz et. al. 1995). An example of this mapping is shown in Figure 3. As can be seen in the figure, the front face of the sensor cube maps to cells (13, 14, 15), (4, 5, 6), and (22, 23, 24).

As the agent moves about the work volume, the sensor patterns associated with the local neighborhood are monitored. If the pattern matches that of a given "building rule," then the rule is activated and the corresponding building action is taken.

Figure 4 illustrates a simple example in which two rules are utilized to build a column structure. The first rule can be interpreted as, "if a blue (dark) block is the only object within the sensor lattice, and it is directly above the building agent, then deposit a green (light) block." Similarly, the second rule also calls for the deposit of a green block, but only if a green block is detected directly above the agent. Finally, as can be seen in the figure, a total of eight building agents were active in the assembly of the column. Each builder acts independently, and is essentially unaware of the activities of other builders, except when a new block is deposited (detected as change in sensor lattice) or if two builders attempt to move into the same physical location – which triggers the collision avoidance mechanism. A simplified block diagram of the assembly procedure is shown in Figure 5. The basic algorithm repeats the pattern .. move building agent .. check for rule match .. deposit block (if rule satisfied) .. move building agent, and so on. The building agents, which can vary in number, must be initially located within the work volume. It is assumed that the initial position of the building agents is not in the immediate vicinity of the building seed block, which by default is always located at the origin. As indicated in the flowchart, agent locations are updated and the sensor patterns are compared to the set of assembly rules. Note that the agents are only allowed to move into a neighboring cell (one of the 26 surrounding cells in the agent's local 3 × 3 × 3 cell lattice) during a single iteration.

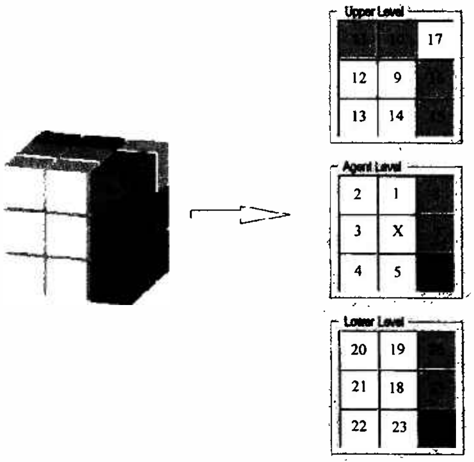
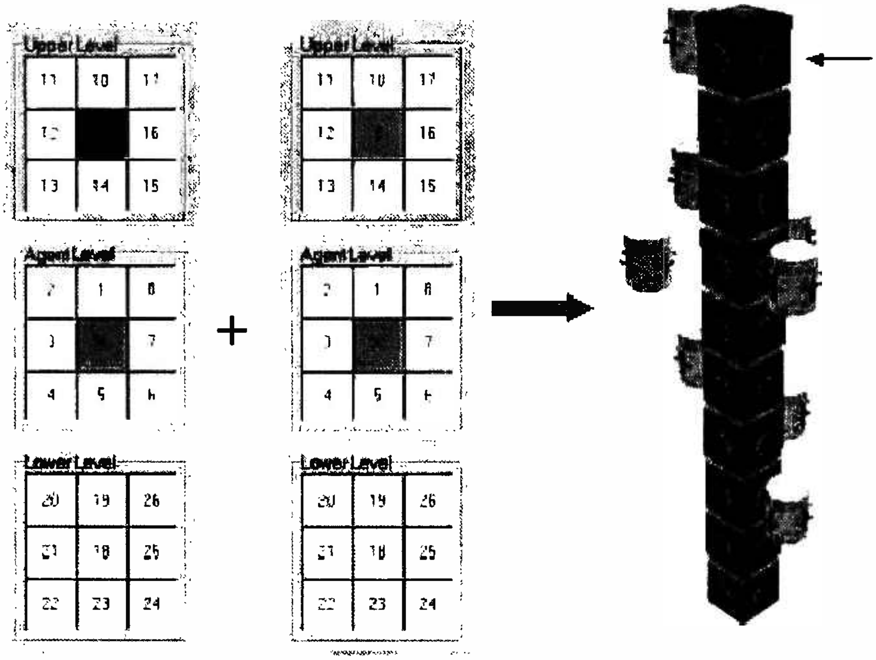


Figure 3. Sensor Lattice Mapping.



"Seed Block" used to initiate building process.

Figure 4. Simple Builder Rule Example.

Initially, the agents are located some distance from the seed block. One possible method of searching the work space for cell locations in which the agent's sensor patterns match a rule is to simply allow the agent to perform a random walk through the work volume. Unfortunately, such a scheme is very inefficient. Consider a work volume that extends 100 cells along each axis. This corresponds to a volume containing 1,000,000 cells. Initially, only the 26 cells bordering the seed block are candidates for block deposition, and typically only one of the 26 will satisfy a building rule. The statistics of this type of 3-dimensional random walk are quite complex; however, it is safe to say that on average, many thousands of iterations would be required to locate the correct initial position for depositing a building block. This fact was borne out with a series of simulation trials. In 19 of 25 simulation cases, the agent performing a random walk in the work volume failed to locate the seed block within 10,000 iterations. The earliest the seed block was found using the random walk approach was in approximately 4,000 iterations. Clearly a more effective search procedure is required.

In nature, insects utilize a variety of methods to provide them with a sense of direction and location (e.g., sunlight angle of incidence, chemical markers, etc.). If we allow the seed block to somehow publish its approximate location to the building agents, then the size of work volume that must be searched can be drastically reduced. An example of how this could be accomplished would be to place a light source upon the seed block, and instrument the robotic agents with light detectors. Essentially, the agents would simply move toward the light until they are in close proximity of the seed block. Once the agents are within a predetermined range of the seed block (perhaps determined by the measured intensity of the light source), they could begin searching for cell locations corresponding to sensor patterns that match a rule in the rule set.

While interesting structures can be assembled with a totally homogeneous population of agents, greater efficiencies can be achieved by allowing for specializations within the population. This can be accomplished by allowing different members of the population to follow different rule sets, or in effect, creating population subclasses. Delaying the introduction of certain classes into the work volume has also proved beneficial in controlling the coherence of the building process. A coherent set of assembly rules is defined as a rule set that disallows ambiguity in the building process, and thereby generates identical structures given different initial agent conditions (Mason 2002). Significant improvements in the efficiency of the building process were obtained by using a contact, or crawling, algorithm which restricts the searching agents from leaving the surface of the structure once located.

Simulation Results

In the preceding sections, the architecture of an assembly strategy for the autonomous robotic construction of large space structures was developed. Results obtained by applying the algorithms and software to the assembly of a test structure will now be examined. A planar platform penetrated by a central beam was the architectural design goal for the test case. This structure notionally represents a Solar Power Satellite, but the underlying algorithms are applicable to a wide variety of assembly tasks.

Figure 7 illustrates the building process of the targeted structure with selected simulation screenshots and

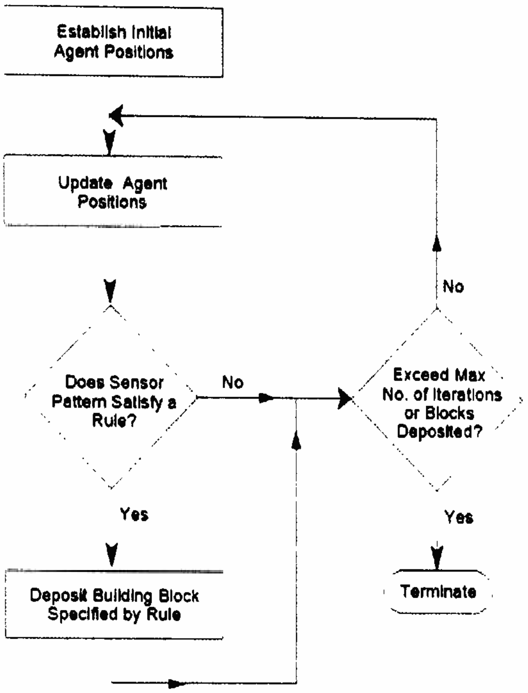


Figure 5. Simplified Building Algorithm.

the corresponding rule most recently triggered by the local configuration. This structure was assembled using a building rule set containing 43 individual rules. For this example, the agent population was completely homogeneous in that each agent operated with the exact same rule set. As can be seen in the figure, there were 8 building agents present, and after 17 iterations the first block was deposited (the triggered rule is adjacent to the sub-figure). The central planar section was complete after 40 iterations, and by iteration 175 the central beam was beginning to emerge. The complete planar platform was complete by iteration 402, after which only the central beam continued to be assembled.

Figure 6 illustrates a more complicated structure under construction. A non-homogeneous agent population was utilized for this example, with three different agent classes defined by three different rule sets. A phased introduction of the agents into the work space was also used in this example to simplify the coordination of the assembly process, (e.g., rim building agents were not introduced until the spoke builders had completed their task).

It is important to note that the number of building agents taking part in the assembly process does not effect the final geometric shape (morphology) of the structure. In general, the build time, or number of iterations, is greater when fewer agents are working. Conversely, the more agents present, the quicker the build time.

Hardware Demonstrations

Several hardware demonstrations of the assembly procedures are underway at the present time. In order to minimize hardware requirements and complications, a global vision system is being employed. This system utilizes an object detection algorithm to examine the entire work volume. The global object location information is transformed into the local sensor lattice of each agent, followed by pattern matching logic to assist in the all important task of deciding whether or not a rule has been satisfied. This global to local transformation of the configuration state of the structure is illustrated in Figure 8.

Summary

Construction of future large space structures will potentially be performed primarily by robotic means; however, many aspects of required robotic systems have yet to be developed. The research presented herein focuses upon the development of an autonomous control architecture in which individual robotic assemblers cooperatively construct the target structure. This form of decentralized coordination based upon biologically inspired principles appears promising, as was demonstrated by the simulations.

The control strategy employed by the individual robots utilizes short range sensing in conjunction with a relatively simple set of construction rules to govern the building process. Direct communication between the robotic building agents is minimal, or even non-existent. Coordination of the building process is an inherent property of the system since the construction rules are activated by local sensing of structural configuration. An advantage of this type of cooperative behavior is that massive redundancy is automatically built in to the system. Failure of a particular individual building agent (robot) will only slow the building process, not stop it. The required computer processing power of the individual agents is reduced by the fact that the overall design, or blueprint, is not maintained, or even understood, by the agent. The stigmergic building algorithm produces the final design as an emergent system property.

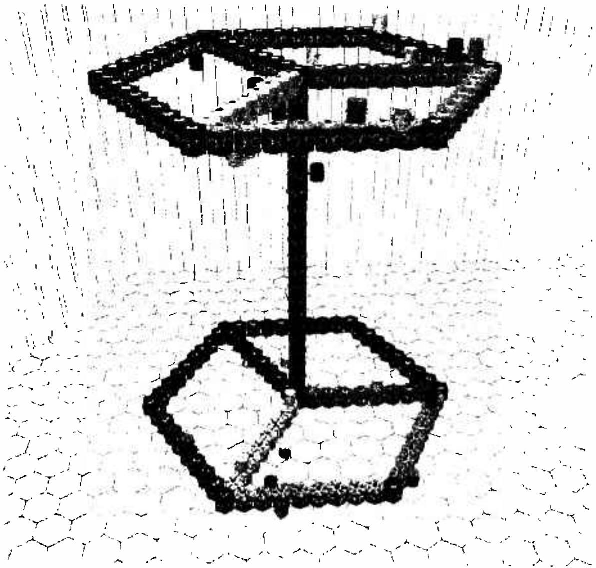


Figure 6. Structure Produced by Non-homogeneous Population of Agents.

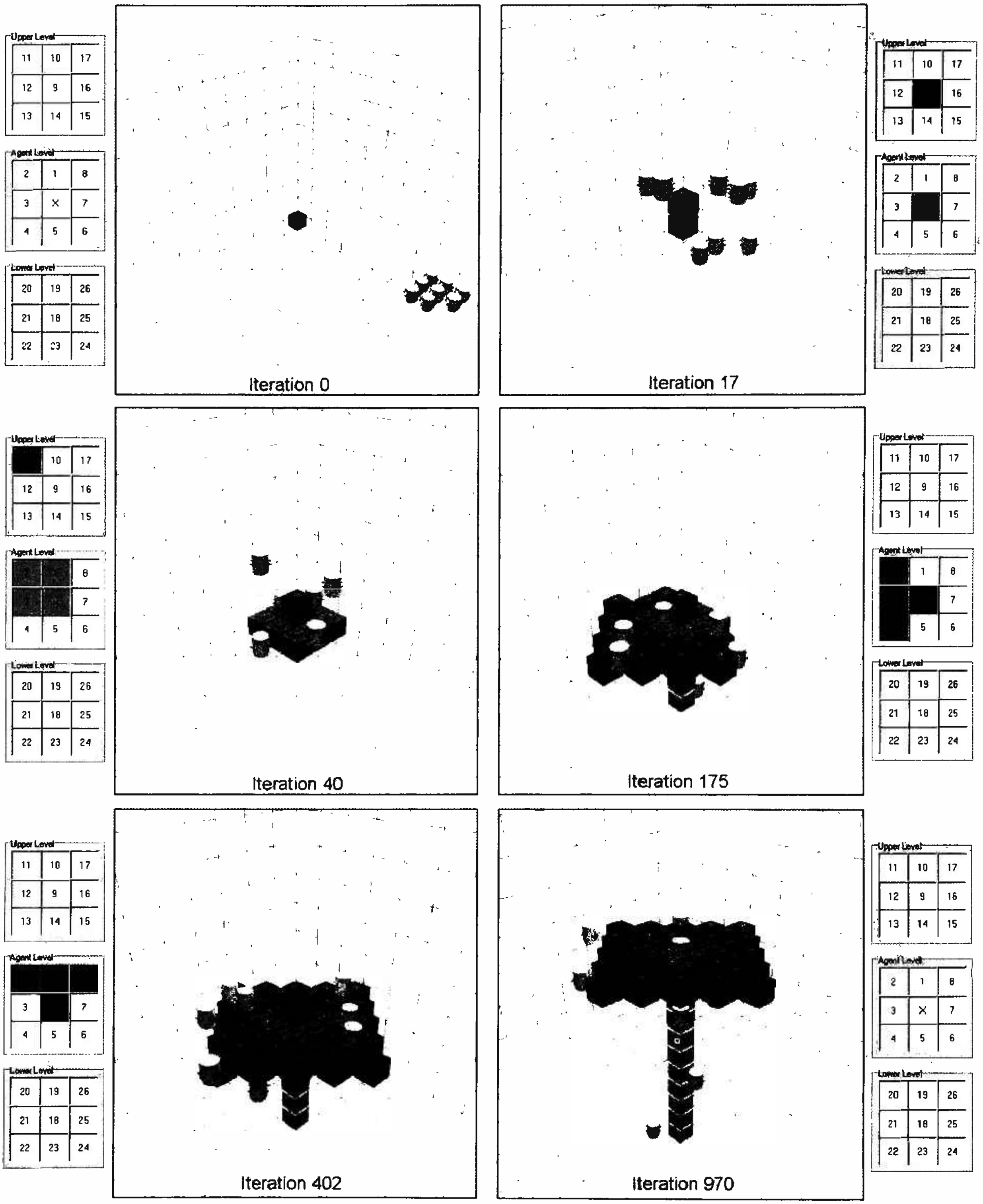
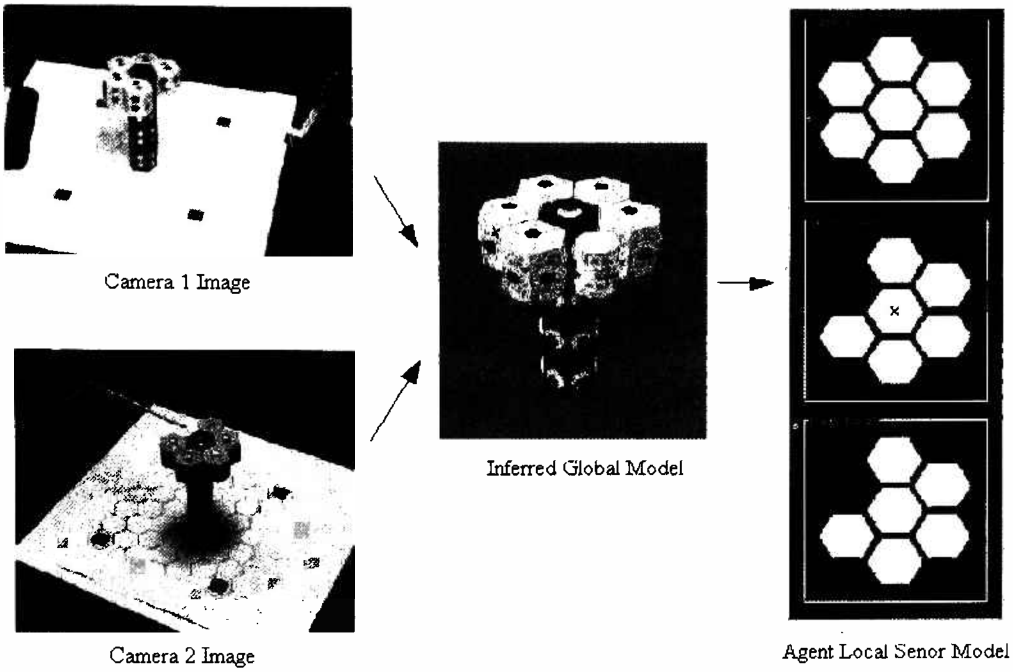


Figure 7. Structural Assembly Process of SSP Prototype.



Camera 1 Image

Camera 2 Image

Inferred Global Model

Agent Local Senor Model

Figure 8. Global to Local Object Transformation Used in Hardware Studies.

Acknowledgement

The authors would like to thank NASA for sponsoring this research.

References

Beckers R., Holland O. E., and Deneubourg J.-L., "From Local Actions to Global Tasks: Stigmergy and Collective Robotics". In Brooks R. and Maes P., editors, Proc. of the Fourth Workshop on Artificial Life, Boston, MA, July, 1994, The MIT Press, pp. 181-189.

Lake, Mark S., "Launching a 25-Meter Space Telescope: Are Astronauts a Key to the Next Technically Logical Step After NGST?", IEEE Aerospace Conference, Big Sky, MT., March 10, 2001, Paper No. 460.

Mason, Z., "Programming with Stigmergy: Using Swarms for Construction," Artifcial Life VIII, Standish, Abbass, Bedau (eds), MIT Press, 2002, pp 371-374.

Mataric, M.J., "Issues and Approaches in the Design of Collective Autonomous Agents," Robotics and Autonomous Systems, v. 16, 1995, p. 321-331.

Theraulaz, G. And Bonabeau, E., "Modeling the Collective Building of Complex Architectures in Social Insects with Lattice Swarms," Journal of Theoretical Biology, v. 177, 1995, p. 381.

Valckenaers, P., Kollingbaum, M., Van Brussel, H., Bochmann, O., Zamfirescu, C., "The Design of Multi-Agent Coordination and Control Systems using Stigmergy." Proceedings of the IWES'01 Conference, Bled, Slovenia, March 12th - 13th, 2001.