

# Chapter 4

## Continuum Mechanics for Coordinating Massive Microrobot Swarms: Self-Assembly Through Artificial Morphogenesis

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### **ABSTRACT**

*This chapter addresses the problem of coordinating the behavior of very large numbers of microrobots to assemble complex, hierarchically structured physical objects. The approach is patterned after morphogenetic processes during embryological development, in which masses of simple agents (cells) coordinate to produce complex three-dimensional structures. To ensure that the coordination mechanisms scale up to hundreds of thousands or millions of microrobots, the swarm is treated as a continuous mass using partial differential equations. A morphogenetic programming notation permits algorithms to be developed for coordinating dense masses of microrobots. The chapter presents algorithms and simulations for assembling segmented structures (artificial spines and legs) and for routing artificial neural fiber bundles. These algorithms scale over more than four orders of magnitude.*

DOI: 10.4018/978-1-5225-5276-5.ch004

## **GOALS**

Although there has been considerable progress in the bulk assembly of nanostructured materials, many future applications of nanotechnology will require the assembly of complex hierarchical systems, structured from the nanoscale up to the macroscale. Examples include future robots, computer systems, and peripheral devices. In some cases, technologies such as 3D printing will permit the fabrication of systems of moderate complexity. However, hierarchical systems that span the full range of scales, from nano to macro, will require self-assembly, at least at the smallest spatial scales.

The fabrication of biological-scale robots illustrates many of the issues: how can we assemble a brain-scale artificial nervous system, high-resolution sensors, effector systems with many degrees of freedom, and so forth? Mammalian brains contain billions of neurons with trillions of interconnections, and it is plausible that artificial neural systems with similar capabilities will require comparable numbers of devices. Mammalian cortex is highly structured and functionally organized; how can we assemble comparable numbers of devices and interconnect them appropriately? For example, the human retina has perhaps 100 million receptors, which compress data into the approximately one million neurons of the optic nerve; we would like to be able to assemble sensors of similar complexity for future robots. Animals behave competently in the physical world by means of detailed proprioceptive, haptic, and other sensory information, which is used to control, in real time, a large number of muscle fibers to achieve fluent, finely controlled, and rapid movement. How can we assemble sensor and effector systems of comparable complexity?

We are investigating the use of swarms of microrobots to assemble such systems, but to do so we need techniques that will scale up to massive (biological) numbers. There is no specific goal number, of course, but we have at least hundreds of thousands in mind, and millions or billions may be required to assemble biological-scale robots. We cannot assume that coordination and communication strategies that work with hundreds, thousands, or even tens of thousands of microrobotic agents will scale up to biological numbers. As is explained in more detail later, we guarantee that our methods will scale by using the same approach that biologists have used for describing the movement of massive numbers of cells: partial differential equations. In effect, we approximate massive numbers of agents by the continuum limit: an infinite number of infinitesimal agents.

We do not know what sorts of microscopic agents will be used for the self-assembly of complex, hierarchical systems; possibilities include microrobots, nanobots, and genetically-engineered microorganisms (effectively organic microrobots). Since there are a variety of possible technologies at various size scales, our goal is an abstract description, independent of the specifics of the agents. That is, we are developing

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