Pattern Formation in Mobile Computational Particles with Minimal Capabilities

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1 Introduction

Over the next decades, MEMS and nano-sensors will be everywhere. In this perspective, we envision the possibility of exploiting these technologies to build sorts of multi-cellular computational organisms, made up of millions of interacting autonomous computational particles, capable of assembling and dynamically re-assembling themselves into a variety of complex shapes (as the T1000 robot in the Terminator 2 movie). From a software perspective, the critical task is to identify appropriate (self)organization principles and programming methodologies for controlling the overall behavior of such complex systems. In particular, our goal is to study how and to which extent a group of mobile autonomous particles with the only capability of locally interacting with wireless links can be programmed to coordinate their respective movements to create variety of global shapes.

2 Morphogen Gradients

Motivated some previous works [1], we tried to recreate in our scenario the biological mechanism of morphogen gradients: proteins diffused along the length of an embryo driving morphogenesis. Reproducing this mechanism in dense network of short-range wirelessly interacting particles is dramatically simple. A “source” particle can create a gradient by broadcasting a simple message, containing the morphogen name and a value, initially at zero, to all nodes within the wireless connection range. Neighboring particles recursively store and re-broadcast the message, incrementing its value, until the gradient has propagated across the entire population. This simple mechanism can be used in powerful ways: (i) the value of a morphogen gradient stored by a specific particle gives a measure of the particle distance from the source of the gradient. A perceived value of \( n \) steps implies a distance \( nr \) from the source, where \( r \) is the wireless communication range of particles (the quality of this estimate depends on the density of particles). (ii) if more than one particle emits the same morphogen gradient, the gradient value reflects the shortest distance to any of the sources. Thus, if a circle of particles emits a gradient then the value increases as one moves perpendicularly away from the circumference. (iii) if a particle can perceive the local slope of any gradient, it can also move following the gradient downhill to approach the gradient source.

3 Experiments

In our research [1], we have been able to achieve a variety of shapes with the morphogen gradients approach. All the results have been tested on a simulator for large-scale mobile ad-hoc networks developed within our research group (see figure 1, 2, 3, 4, 5). All the figures from (a) to (d) show different stages of the establishment of a specific pattern or shape in a cloud of randomly distributed particles. Despite these promising results, a number of open directions are still to be investigated. Currently we are trying to define a simple and modular programming model, enabling designer and programmers to enforce in a modular and compositional way a variety of complex pattern.

References


Figure 1. BARYCENTER (Center of Gravity) ELECTION.

The barycenter is the particle that minimizes the sum of the distances from all the other particles. It can be elected by having all the particles propagate a morphogen gradient. By adding the values of all the gradients, particles know the sum of the distances from all the other particles. Each particle can compare its computed value with neighbors’ ones. The one having the minimum is the barycenter. Due to propagation delays, as the system evolves, some particles (in black) may temporarily consider themselves the barycenter. At the end only one barycenter is elected.
Figure 2. CIRCLE. Once elected, the barycenter can propagate a 'circle' morphogen gradient. Some particles (in black) already recognize themselves as being at the correct distance from the center and do not move; the other particles gradually collapse toward the circle circumference, by following downhill the 'circle' morphogen gradient.

Figure 3. RING. This algorithm starts like the circle one, but the particles recognizing themselves at the correct distance from the barycenter, propagate a 'ring' gradient. Inner particles follow downhill this gradient to approach the border or the circumference creating the central hole of the ring.

Figure 4. MAKING LOBES. Here we tried to break the circular symmetry of previous experiments and let lobes emerge in the global shape. Particles on high-density regions propagate the circle gradient without increasing its value. This lets the circle gradient reach, in some areas, the intended radius farther away from the source. Thus, the circle shape is deformed and lobes appear.

Figure 5. POLYGONS. By controlling the emergence of lobes via a leader-election mechanism, polygon shapes can be created. For example, three leaders deforming the circumference to make a lobe, let the creation of a triangle.