Towards self−organising robot formations : a decentralised approach

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Abstract
This paper introduces a new class of locally connected mobile automata networks where each node changes its internal state vector depending on the information it receives from its neighbours. The configuration of the internal states is then translated to the propulsive motion of network's elements. The research aims (i) to investigate how collective decision−making and processing can be achieved with a set of simple mobile agents and (ii) to implement real−robot experiments with collectives of robots, communicating via wireless local area network (WLAN). This paper demonstrates how a large number of agents form a line segment only using local information. The agents are not allowed to communicate with more than two other agents at any time. The performance of the algorithms is demonstrated by simulation.

1 Introduction
How do coherent global behaviours emerge from the collective activities of relatively simple and locally interacting agents? Nature supplies us with many examples of animal societies which collectively carry out complex tasks, exhibit synchronised motion and make decisions. Social insects such as ants, termites and bees display at the level of the colony a wide range of behaviours, for example army ants organise impressive hunting raids. Colonies of social insects can provide the inspiration as natural prototypes for a self−organising robotic network (Bonabeau *et al*, 1999).

Melhuish *et al.* (1998) were inspired by these natural systems and searched into the idea of object sorting using minimalist robots and algorithms. They used stigmergy to achieve self−organising behaviour in collectives of mobile robots. An alteration in the environment made by one robot will influence subsequent behaviour of other robots. Agents solely use information about their environment and can only communicate through the environment to achieve puck−sorting. They don't rely on explicit inter−agent communication.

Emergent behaviour is not specified explicitly in any global control system but instead arises from the interactions between robots, each executing local rules. Each agent in the collective does not appear to be provided with a blue−print, an internal world model, of what the construction should look like. Macroscopic structures are said to be a consequence of the interaction between simple agents acting according to some simple rules (Bonabeau *et al.* 1999). What are the salient ingredients required in the design of collective behaviour? Internal states and sensor readings of neighbouring units could be used as input to the robot's behaviour module. This paper aims to model a robotic system where each robot broadcasts its internal and external states, its sensor readings, to its nearest neighbours.

Complex systems theory can provide an understanding of the dynamics of interacting agents. Beni *et al*. (1991) phrase the problem of interaction as follows: "*the essence of the DRS (distributed robotic system) problem is to design a system that while composed of unintelligent units, is capable, as a group to perform tasks requiring intelligence − the so−called 'swarm intelligence'*".

Complex systems consist of a large number of entities which have strong interactions between each other. Economies, biological cells, road systems, stock markets, cellular automata and collectives of robots are all examples of complex systems. Self−organisation is often linked with complex systems, the idea is that the basic elements somehow organise themselves into a higher level units or structures. Cellular automata form a framework where problems, related to complex systems, dynamics and computation, are successfully tackled. Many−body systems have been successfully modelled using cellular automata theory such as gas models, traffic simulation etc. (Chopard *et al.*, 1998).

Cellular automata theory is subject of much current research but has been difficult to apply to actual robotic systems. This research aims to preserve the key physical features of a robotic system in the model. Beni *et al*. (1988, 1991) describe the concepts of cellular robotic systems but their robotic system also retained the CA feature of discrete cellular space. This research attempts to model a network of locally connected robots more realistically. The feature of discrete cellular space is abandoned and our concentration is focused on the local interactions between robots using explicit communication.

A mobile automata network may be seen as a set of elementary processing units, where every unit moves in a physical two− or three−dimensional space. Each processor is capable of communicating with a limited number of other processors on a local basis. The number of neighbours of any processor in the network is several orders less than the total number of processors in the network. Each agent, or processor, takes a few internal states and external states and computes what action to take from this local information. Restricted memory of the processors and diffusion−like information transfer are essential features of mobile excitable networks (Adamatzky and Holland, 1998) (Adamatzky and Melhuish, 2000). The problem of coherent activity of mobile units would benefit a wide range of disciplines and may prove to be particularly important in the design of future distributed robot systems which employ electro−activated polymers (Kennedy *et al*, 2001).

Additionally, we define the connectivity C of the overall network as the number of edges, or communication links. For n robots C lies in the interval $0 \le C \le \frac{1}{2}n(n-1)$. By allowing each robot to communicate only with at most two other robots means that the total number of connections is kept to a minimum and therefore networks of locally connected robots are more attractive from an engineering point of view. Limiting robots to two communication links means that the connectivity C will lie in the interval $0 \le C \le n$ for such systems.

The next section gives a formal description of the framework used in this paper. Section 3 presents some experimental results and developed algorithms. Section 4 discusses the model and results of the experiments from an roboticist's point of view. Section 5 presents the ultimate goal of this work.

2 Mobile automata networks

One−dimensional cellular automata (CA) are perhaps the simplest examples of decentralised, spatially extended systems in which computation can be observed. The CA rule states how each cell is updated according to the states of its neighbourhood. A neighbourhood consists of a cell and its *radius r* neighbours on either side. (Chopard *et al.*, 1998, Adamatzky, 1994).

This basic feature of neighbourhood in automata models is used to build robot systems capable of self−organisation. State and motion updates of every agent are directly coupled to signals and information received from other robots. Updates purely made according to the states of the neighbourhood are clearly insufficient in an attempt to model mobile automata networks. Robots need sensors to enable them to perceive their environment. According to (Beni 1988) robots are entities that are capable of processing *matter* and *information*. Beni defines the capability of processing matter as *the capability of transferring matter, either their own (via locomotion) or of other objects (via manipulation) or both*.

Let us now define a framework in which we may be able to apply ideas and methods used in cellular automata theory and complex systems theory in general.

Model

A mobile automata network is a tuple <G, Q, W, P, u, f, g, h>, where G is a regular graph, G=<X, E>, in which X is a set of nodes, E is a set of edges and |X|=n is the number of agents (Adamatzky, 1994). Each node of the network is connected with k nodes, possibly including the node itself, determined by a connection template, or a neighbourhood, u: $X \rightarrow X^k$. The nodes update their states simultaneously in discrete time, depending on the states of their neighbours, by the following functions: node state−transition function f: $Q^k \rightarrow Q$, state−to−velocity transformation g: $Q \rightarrow W$, and collision function h: $P^n \rightarrow P$. Nodes of the network update their states depending on the states of their neighbours using the function f. This function can be represented by various techniques, for example, via arithmetical operators if elements of Q are arithmetical numbers or lookup tables. However, in this paper the functions are represented by if−then notations.

Elements of the set Q are called internal states and are typical automata states, e.g. Symbols or integers. The elements of the sets W and P are referred to as external states, W is a set of vectors and the elements of P are the positions of network nodes in space. At each step of the simulation, the internal state of a node is translated to its velocity vector. The velocity vector is modified by the collision function to reflect the realms of the physical world.

Every node in the network should be able to detect obstacles in space. Automata models only process information, this is clearly insufficient since a mobile robotic system must also process environmental cues as an essential function of the system. Beni (1988) speaks of the ability of robotic systems to process matter. To allow model to detect obstacles in space, we simply add an additional set I of input states and modify the node state−to−velocity transition function as follows: g: $Q \times I \rightarrow W$. The function h and the set P have been included to facilitate the implementation of a simulation but would become redundant and inapplicable in a real−robot implementation.

Constructing logical systems and diffusion−like information transfer allows computation in such networks. In an attempt to understand the principles of structure formation in collectives of minimalistic mobile agents, a simulation of this model has been written in order to test this framework.

3 Simulation experiments

The purpose of these experiments is to investigate the possibilities of controlling a collective of mobile agents in the framework of mobile automata networks. The experiments have all been carried out in simulation and are designed to test the model and the developed algorithms.

Experimental scenario and assumptions : an agent can sense the relative direction of the signals of the neighbouring agents. An approximate distance can also be obtained from these signals. In the simulation some noise has been added to the true positions of the neighbouring agents. The problem of structure formation can be regarded as a search for the mapping between the agents' simple stimulus−response rule−sets of local actions based on the local sensor information and the resulting structure formation.

The inspiration for the first experiment came from an article describing the ancient Roman surveying tool *groma,* used by groups of surveyors to align themselves into a straight line between two cities. The point being that each group of surveyors could only detect the two neighbouring groups. However, from this local sensing a straight line was created (BBC, 2001). Although in the first three experiments no explicit information is exchanged between robots, information about relative direction and distance to neighbours is obtained from the received signals. The agent's motion is calculated from simple, geometric relationships between the agent and its neighbours. A typical vector update can be seen in figure 1(a). The agent's sense of direction is shown in figure 1(b).

(a) (b)

Figure 1 : vector update

Every agent can sense the relative origin of the signals received from the two neighbours. For example, if signals are perceived to come out of directions 3 and 5, the agent chooses to move in direction 4.

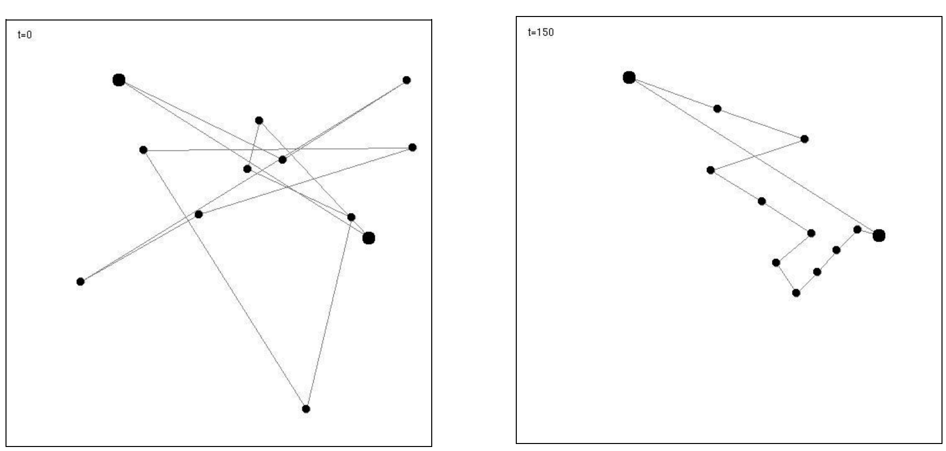
Different approaches to spatial self−organisation have been proposed (Unsal 1993, Sugihara and Suzuki 1990) but the approach discussed in this paper differs in so far that we only use local information. Melhuish (2000) introduced the term *autostruosis* in an attempt to clarify the vocabulary of construction, which includes terms such as self−organisation, self−assembly, emergence and autopoesis, illustrating that constructions can be made from robot bodies.

Experiment 1

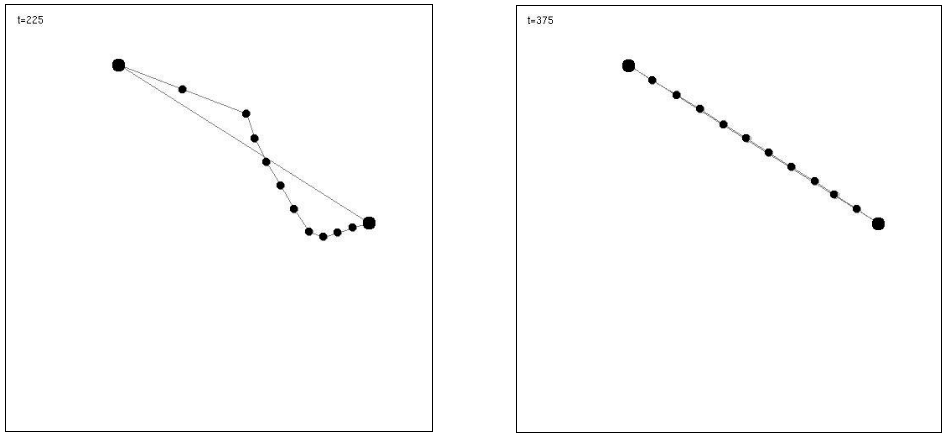
In this first experiment, the neighbourhood of the processor is fixed and set by a non−physical communication graph, the agents will only be allowed to communicate with two other robots. The agents try to form an angle of 180 degrees whilst trying to maneouvre themselves between their neighbours. The rule set is minimalist:

Move between the two neighbours always trying to achieve an angle of 180 degrees.
Move towards neighbour that is furthest away.

The possibility of losing communication capabilities is disregarded and the communication range is unlimited. Furthermore, two agents are immobilised, serving as the two end points of a line segment, represented by the large dots in figures 2(a−d). The agents' starting positions are chosen at random. The Figures 2(a) and 2(d) show the agent's starting and end positions respectively. Figures 2(b) and 2(c) show intermediate stages of the experiment. The lines in the figures describe the communication links between robots. As the communication graph is fixed, each neighbour is communicating with its topological neighbours.

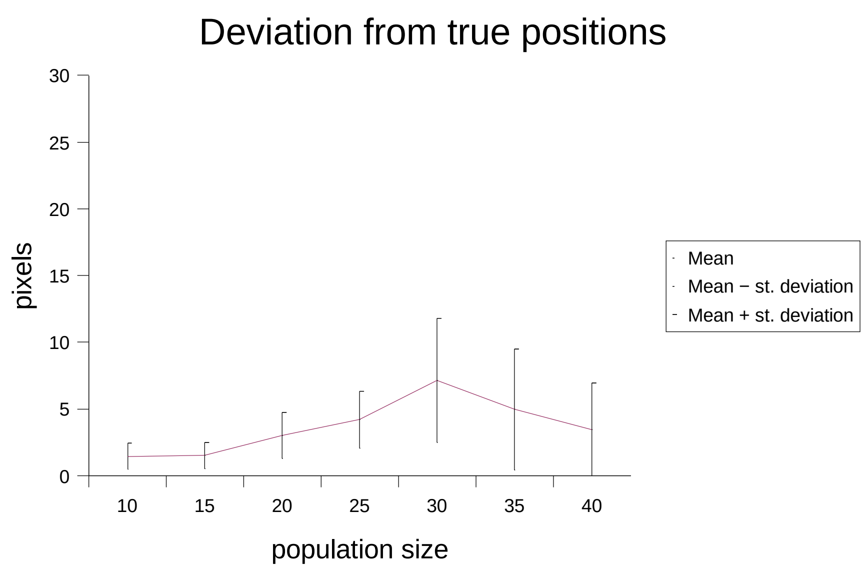


(a) t=0 (b) t=150



(c) t=225 (d) t=375

Figure 2 (a−d) : Line formation between two fixed end points



Graph 1 : Mean Euclidean distance error

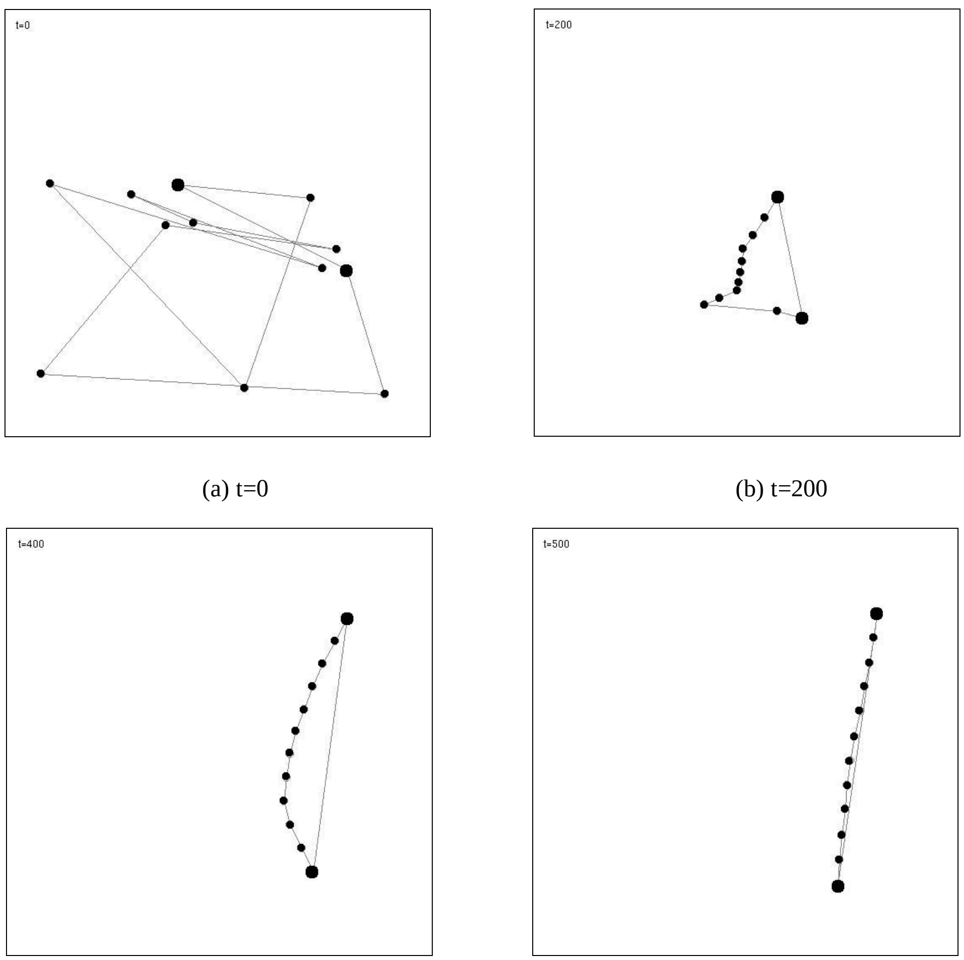
As seen, 10 agents successfully align themselves between the two fixed end points. The second rule allows the agents to position themselves at equal distance from their two neighbours. Several repetitions of this experiment have shown that the agents will distribute themselves equally−spaced between the two end points. The distance between robots is approximating d/(n−1) where d is the distance between the two end−points and n is the total number of agents, including the two end−points. It seems that the line formation is a fixed point attractor in the space−time dynamics of the system. Graph 1 shows the mean error in the Euclidean distance between the expected positions and the true positions of all agents. However, no conclusive statement can be made as only five runs for each population size were carried out. A complete statistical analysis of the results of this experiment are in preparation.

Experiment 2

Can locally interacting agents form a line in free space when the two end points are not fixed? Again, two agents are chosen to act as end points but are allowed to move in space. These two agents try to maintain a distance d from their neighbours.

If agent has two neighbours:
Move between the two neighbours always trying to achieve an angle of 180 degrees.
Move towards neighbour that is furthest away.
If agent has only one neighbour:
// Move within a certain distance to your neighbour and keep that distance.
if(distance<threshold)
    move away from neighbour
else
    move closer.

Figures 3 (a−d) show the line formation with two freely moving end points.



(a) t=0 (b) t=200

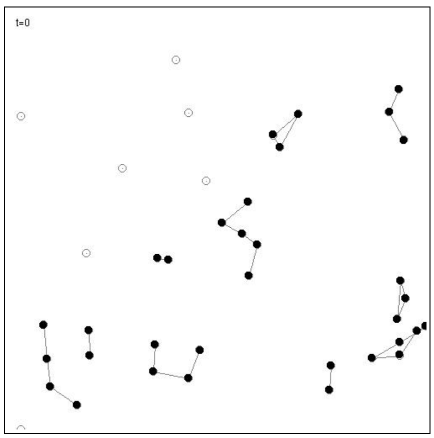
(c) t=400 (d) t=500

Figure 3 (a−d) : Line formation between two free moving agents

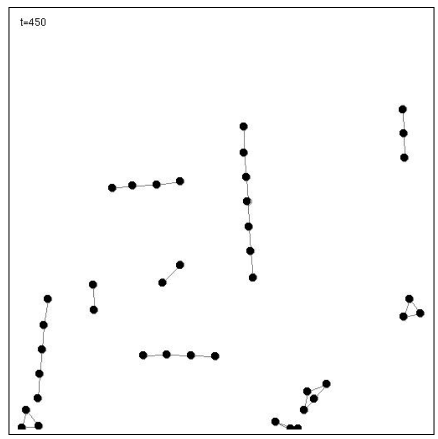
The line segment is dynamically stretched in order to include all agents. In the previous experiment, the agents distributed themselves uniformly between the fixed end points. During this experiment inter−robot distances approximated the distance the outer agents tried to maintain from their neighbours.

Experiment 3

The fixed neighbourhood set by the non−physical communication is removed in order to model a more realistic scenario. The agents build up communication links, two at maximum, according to physical proximity. We assume that the agents' communication range is limited and that communication links cannot be uphold over large distances. As in the previous experiments, the agents are randomly positioned in an enclosed environment at the start. The same rules as in the previous experiment apply. Figures 4 (a−b) show the formation of several smaller lines. The agents very quickly build up communication links with their nearest neighbours and the formation of several small sub−networks can be observed. Some agents form ring−like networks and fail to form line segments. The next experiment aims to control the line formation using simple diffusion−like information transfer.



(a) t=0



(b) t=450

Figure 4 (a−b) : Formation of smaller line segments

Experiment 4

The setup for this experiment is somewhat different. This experiment looks into the possibility of forming more complex structures using diffusion−like information transfer within a mobile automata network. The agents are randomly placed into the environment and one agent starts to recruit other agents in order to form a line structure. Every agent holds two integer variables: a *counter* and the *total* number of agents in the network. Every time another agent connects to the recruiting agent, the newly connected agent takes the neighbour's counter value, increments and stores the result as the total number of agents. The agent that has only one neighbour and a higher *counter* value than its neighbour becomes the recruiting agent. For example, if the total number of agents recruited equals 9, the recruitment process is stopped. The information stored by the agents allows to assign a new task to a single agent. Figure 5(c) shows the newly selected robot, now represented by the large dot, which tries to position itself so that it and its neighbouring agents form an angle of 90 degrees.

If agent has two neighbours:
Move between the two neighbours always trying to achieve an angle of 180 degrees.
Move towards neighbour that is furthest away.
Read total variables of neighbouring agents, choose highest, store the result.
If agent has only one neighbour:

```
 // Move within a certain distance to your neighbour and keep that distance.
if(distance<threshold)
        move away from neighbour
else
    move closer.
If agent i connects to the recruiting agent j
counter(i)=counter(j)+1;
total(i)=counter(i);
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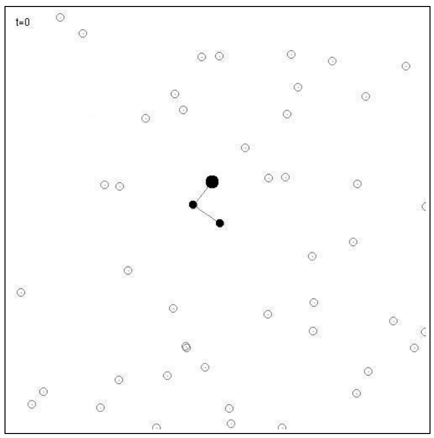
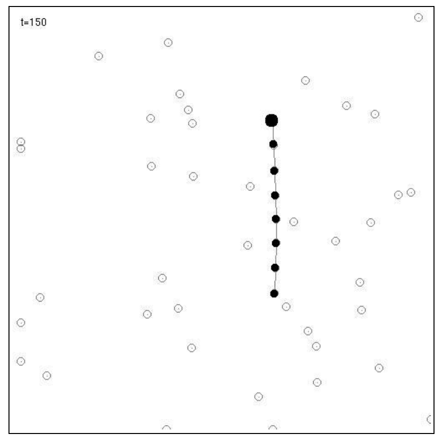
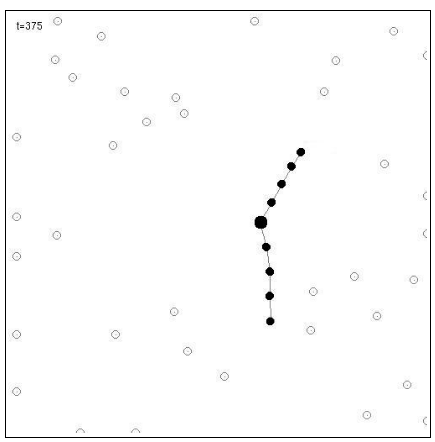


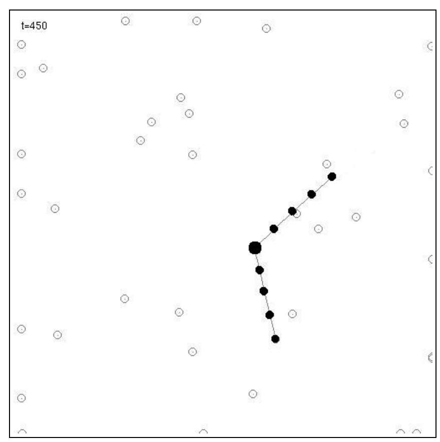
(a) t=0



(b) t=150



(c) t=375



(d) t=450

Figure 5 (a−d) : a more complex structure

A large number of agents was dispatched in order to quickly build up a line formation. These simple rules assure that every agent knows how many agents are currently recruited in the construction process. Once the line has the required length, the agent closest to the mid−point of the line is chosen and starts to move away from its neighbours, pulling the robot chain until the angle is approximating 90 degrees. However, no precautions to avoid failure due to broken communication links were taken when designing this algorithm.

4 Discussion

In this paper we have shown that locally connected agents can form simple structures and more complex structures through diffusion−like information transfer enabling counting. The first two experiments have shown that a number of agents can form a line segment purely based on local information. With regards to experiment 4, a serial strategy may yield the possibility of constructing more complex structures such as squares, spirals, *etc*. Instead of first forming a line, agents could move directly into the required position once they connect and before recruiting new agents. Experiments implementing such an end−active approach to structure formation are in preparation as well as a statistical analysis of the results obtained so far.

CAs update their states synchronously and in discrete time steps. The development of this model requires the solution to theoretical problems such as synchronicity. It is unreasonable to assume synchronicity from a distributed, decentralised robotics point of view. However, no failure occurred in the experiments when synchronicity was disregarded.

The framework presented in this paper is very general and may be applied to many different phenomena, such as velocity matching in swarms, distributed sensing scenarios, processing *etc*. A more thorough investigation into the space−time dynamics and phenomenology of this newly defined model will be necessary.

5 Future work

How robust is such a system to different sorts of failure? Individual failure? Communication failure? Can such a system exhibit graceful degradation with increasing failure of individual agents? Algorithms to assure and increase the robustness of the system will be developed. An *ad hoc* network is a collection of wireless mobile hosts forming a temporary network without the aid of any centralised administration. As seen in the experiments, this is a highly likely scenario in mobile automata networks, therefore routing protocols in ad hoc networks may turn out to be an important tool in transferring information in such networks (Johnson 1994).

Ultimately, this research aims to verify the simulation results with a set of real−robot experiments. A comparison between the real−robot experiments and the simulation will allow the evaluation of the effects of noise and interference. These experiments will be implemented on a reasonably large population of LinuxBots, robots compromising embedded PC−compatible controllers, wireless LAN technology and the Linux operating system.

References

A. Adamatzky, "Identification of Cellular Automata", Taylor and Francis, 1994.

A. Adamatzky and O. Holland, "Phenomenology of excitation in 2−D cellular automata and swarm systems", In Chaos, Solitons and Fractals 9, 1233−1265, 1998.

Adamatzky A. & Melhuish C.," Unconventional mass−parallel controllers for mobile robots: reaction−diffusion and excitable prototypes" 1st International
Conference on Mechatronics and Robotics (M&R) 2000. Vol 1. Pp. 5−10. St. Petersburg, Russia. 2000.

Adamatzky A. and Melhuish C.,"Construction in Swarms: From Simple Rules to Complex Structures" International Journal of Systems & Cybernetics: Kybernetes. V29 No 9/10. 1184−1194. 2000.

Adamatzky A. and Melhuish C.,"Parallel Controllers for Decentralized Robots: toward nano−design" . International Journal of Systems & Cybernetics: Kybernetes. V29 No5/6. 733−745. 2000.

BBC, "Discovering Roman technology", www.bbc.co.uk/history/ancient/romans/tech_02.shtml, 2001.

G. Beni, "The concept of cellular robotic system", IEEE International Symposium on Intelligent

Control, 1988.
G. Beni and J. Wang, "Theoretical Problems for the realization of distributed robotic systems", Proceedings of the 1991 IEEE International Conference on Robotics and Automation, 1991.
B. Chopard, P. Luthi and A. Masselot, "Cellular Automata and Lattice Boltzmann techniques: an approach to model and simulate complex systems", 1998, cui.unige.ch/~chopard/CA/Book/related.html.
E. Bonabeau, M. Dorigo and G. Theraulaz, "Swarm Intelligence − From natural to artificial systems", Oxford University Press, 1999.
O. Holland, C. Melhuish and S. Hoddell, "Chorusing and controlled clustering for minimal mobile agents", In 4th European Conference on Artificial Life, 1997.
D. Johnson, "Routing in Ad Hoc Networks of Mobile Hosts", In Proceddings of the IEEE Workshop on Mobile Computing Systems and Applications, 1994.
Kennedy B., Melhuish C. and Adamatzky A., "Biologically inspired robots" in Y. Bar−Cohen, Editor, *Electro−active polymer (EAP) actuators − Reality, Potential and challenges* (SPIE Press), 2001.
C. Melhuish, O. Holland and S. Hoddell, "Collective sorting and segregation in robots with minimal sensing", 5th International Conference on the Simulation of Adaptive Behaviour, From Animals to Animats, MIT Press, 1998.
C. Melhuish, "Autostruosis: Construction without Explicit Planning in MicroRobots − A Social Insect Approach", In Evolutionary Robotics Vol iii. AAI Books Ed. Takashi Gomi, 2000.
C. Melhuish, "Controlling and coordinating mobile micro−robots: lessons from nature", IMEC’99 Nashville, 1999.
C. Unsal, "Self−organisation in large populations of mobile robots", Masters thesis, Virginia Polytechnic Institute and State University, 1993.
K. Sharman, "A broad−cast based coordination scheme for a system of autonomous robots", Masters thesis, Virginia Polytechnic Institute and State University, 1994.
K. Sugihara and I. Suzuki, "Distributed motion coordination of multiple robots", IEEE 5th International Symposium on intelligent control 1990.
A. Winfield and O. Holland, "The application of wireless local area network technology to the control of mobile robots", In Microprocessors and Microsystems 23 (2000) 597−607, 2000.
A. Winfield, "Distributed sensing and data collection via broken ad hoc wireless connected networks of mobile robots", In Distributed Autonomous Robotic Systems IV, Parker L.E., Bekey G. and Barhen J., Eds., 273−282, 2000.