Conditional development of bacterial based swarm intelligent systems and real biological manipulation

Angel Goñi Moreno
Natural Computing Group - Universidad Politécnica de Madrid
28660 Madrid, Spain
e-mail: agmoreno@gcn.upm.es

Paula Cordero Moreno
Natural Computing Group - Universidad Politécnica de Madrid
28660 Madrid, Spain
e-mail: p.cordero@alumnos.upm.es

ABSTRACT

Self organized systems have been widely studied during the past decades. The definition of a concrete collective behavior in a population and the interaction between the individuals is known as swarm intelligence (SI). By observing natural conducts, some SI models that are very popular nowadays have been developed recently like Ant Colony Optimization or Artificial Bee Colony algorithms. The aim of this paper is to describe the existing relationship between the advances in bacteriology research and the properties of bacterial communities which are useful for multiagent systems and SI developments. Bacterial populations present a powerful set of communication/interoperation protocols and are the most primitive example of SI. In this work it is presented the necessity of a concurrent and symbiotic work in the two different ways of designing multiagent bacterial based systems: computer SI models and real bacteria manipulation.

Keywords

Bacterial Communities, Swarm Intelligence, Synthetic Biology, Algorithm Development.

1. INTRODUCTION

The study of the various natural processes is being in the last years a source of inspiration of incalculable value in different investigation areas like DNA computing, membrane computing, synthetic biology, artificial neural networks or genetic algorithms. In those cases in which we want to find the optimal behavior of several agents in a community we can base our developments on a swarm intelligence model.

The main characteristic of swarm systems is that the behavior of the entire community is totally different from the behavior of a single agent due to the complex relationships between them. In the case of ant colonies [1], It seems difficult and interesting to understand how almost blind animals, moving approximately randomly, can find the shortest way from its nest to the food source and return.

Other amazing example of swarm intelligence is found on bacterial communities [2][3] whose communication mechanism will be explained in this paper. The reason for turning the research efforts towards the natural behaviors seen on nature it is of relative common sense: the nature has had more than a million years to purify algorithms that assure an optimal use of the resources during the functions of survival of species. Moreover, the incredible autonomous capacity of bacterial communities is a very desired feature to achieve on silicon devices.

The methodological philosophy in which swarm intelligence models are included is called emergence. Emergence is central to the theories of integrative levels and of complex systems. It makes reference to those properties of those processes of a system which are not reducible to the properties or processes of its constituent parts. The emergence concept is related closely to autoorganization concepts and it is defined in opposition to the concepts of reductionism and dualism. The emergence concept has acquired renewed force as a result of the height of complexity sciences and plays a fundamental role in the philosophy of the mind and the philosophy of Biology.

The first part of the paper is used to illustrate how different SI algorithms work and the second part of this work introduce the novel bacterial computing paradigm. This novel architecture based on bacterial communities is quite different from the rest SI models due to its objectives, which are totally different. Obviously, nobody can program or design specific real ants or bees to perform a different behavior but we can program bacteria to carry out desire functions. That difference lead us to reuse the developments in the laboratory in order to engineer SI systems and vice versa.

2. SWARM INTELLIGENCE MODELS

Bonabeau [4] defined swarm intelligence as "any attempt to design algorithms or distributed problem-solving devices inspired by the collective behaviour of social insect colonies and other animal societies". Next there will be explained two of the most famous SI algorimths: Ant Colony Optimization (ACO) and Artificial Bee Colony (ABC).

2.1 Ant Colony Optimization

This model of algorithmic computation was first presented in the doctoral thesis of Marco Dorigo (see url [5]) who in 1996 published three possibilities to solve the well known Traveling Salesman Problem. The main characteristic of Ant Colony Optimization algorithms is the explicit use of elements that belongs to previous solutions. This characteristic was also introduced by genetic algorithms (GA's) which are based on the results returned by previous generations in order to improve the results of the next one. However, in ACO the probabilistic distribution of partial results is explicitly detailed in previous steps without using extra algorithms (like selections and crossovers in the case of GA's).

The communication mechanism of ant agents is a particle set called pheromones. The basic behavior of this agent is to follow the path that has more pheromones and spread them if they find a food source.

Imagine that the ants travel straight to the food. In that case, there is only one path and only one possibility to place the pheromones. If we put an obstacle in the middle of the route used by the ants we will observe how they reach the food by going along the shorter path which avoids the obstacle. The ants that are behind the obstacle can smell the pheromones of the ants in front so they start looking for alternative paths to reach the lost rout. At the very first moment they will try both routs (both sides of the obstacle). That decision is based on the amount of pheromones present in the path. Those ants who first decided to take the shorter path reached the original route before those ants who first decided to take the longer one so the shorter path will be full of pheromones quickly.

2.2 Artificial Bee Colony

The formalization of algorithms based on bee colonies was firstly introduced by D. Karaboga [6]. The most important part of these algorithms is the definition of the communication mechanisms between the bees. As the previous agents, ants, used the segregation of concrete particles, a bee uses its movement to make signals to the rest of the colony. An important part of the hive is the dancing area where the communication among bees take place in order to inform about the quality of food sources.

At the very beginning of the algorithm, a certain bee starts searching around the nest for new food sources. That is because it has no knowledge about the food available in the proximity of the nest. When the bee reaches a food source, the information about the situation and location of it is stored in the bee. After the bee harvests all the possible food it returns to the nest with the information of the quality of the source ready to be communicated to the rest hive agents. Karaboga defined the three options that the bee has when it returns to the nest:

• The bee abandons the food source.
• The bee communicates the information about the new source by its movements.
• The bee continues exploiting the source by itself.

This communication methodology observed on the honey bees is the basis of Artificial Bee Colony optimization algorithms. Some applications of ABC are applied to neural network training [7].

3. BACTERIA COMPUTING

This new century has seen the emergence of a new research area between computer science and biology called synthetic biology. The aims of this new field are the design of not existing biological devices or systems and the re-design of existing natural systems for programmed and desired purposes. The behavior of bacterial communities is suitable for both engineer developments in-vitro and algorithm design in-info. These communities are an example of swarm intelligence and the most primitive organisms in which we can study this computer paradigm. The biggest advantage of the study bacterial networks from the swarm intelligence development point of view is the capacity of bacteria to be build by us in order to perform desire functions. This last characteristic force us to work in parallel in two different places: the laboratory with real bacteria and the computer developing algorithms.

Two related aspects of bacteria communication are the genetic circuits which operations take place inside a cell and bacteria circuits or networks which operations take place in a bacterial community.

3.1 Genetic circuits

In order to develop bacterial based algorithms it is very important to understand how these basic organisms communicate between each other. Among the other styles of SI algorithms this one is the most unknown paradigm due to the recent discoveries about bacterial communication. In spite of being a rather new research area, it is also being developed very fast due to its impressive potential.

Genetic circuits are based on inducible promoters which allow us to switch on/ff the expression of a certain gen. Gen expression is the main principle of synthetic biology. Every gen is a long double DNA strand which codifies a particular information. Those strands are found in higher DNA structures known as plasmids which are circular DNA molecules. In order to make real the information that a gen carries it is necessary to form a protein from such a gen. For example, in order to produce light if the gen codifies fluorescent information (like the famous GFP gene) it is necessary to transcribe the gen into a protein so that the resultant molecule can bright. In conclusion, it is important to know that the active molecules are the proteins and they are the final target of the genetic circuits.

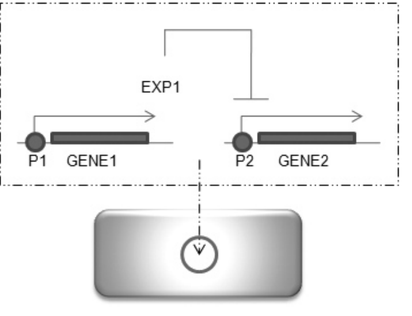

Figure 1. Genetic circuit inside a bacteria

In figure ?? we can observe how a very simple circuit operates. It must be design inside a cell where all the useful molecules to produce the transcription process are (the enzyme in charge of this process is called polymerase) . There are two genes, gene 1 and gene 2 with two promoters in front of them. The promoters are those particles in which polymerase molecules get attached in order to begin the transcription of the following gene. The main characteristic of this circuit can be found in the information that the genes codify. In this example, gene 1 codifies a repressor protein and gene 2 codifies a fluorescent protein.

The repressor protein expressed by gene 1 inhibits the promoter of the second gene so the polymerase cannot join it. That means that whenever gene 1 is being expressed, the second gene will not be transcribed and whenever gene 1 is not being expressed the second gene will be transcribe into a fluorescent protein. This basic circuit is known as a genetic NOT logic gate.

3.2 Bacterial networks

The discovery of bacteria cell-to-cell communication via signal molecules has caused the proposal of the quorum sensing model [8][9]. Before this model appeared, the idea of a successful communication between bacteria and the fact that they could act as a population and not only as single individuals seemed impossible. The bacteria were not supposed to have communication mechanisms that were thought to be restricted to higher organisms. Nowadays, the quorum sensing model is well accepted as well as the fact that groups of bacteria can form complex physical structures known as biofilms [11][12]. Both topics, quorum sensing and biofilms, are now very active research areas in biology and will be soon the objective of major efforts in synthetic biology due to its fascinating capacity to perform computations.

In figure **??** it is illustrated the communication mechanism of bacteria. It is really easy to find similarities between this communication model and the one of ants or bees. They are all based on a emergence behavior.

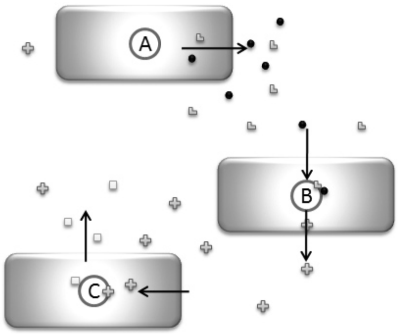

Figure 2. Communication among bacteria

There are four different types of molecules in the space between bacteria and three different bacteria in figure **??**. Bacteria "A" spreads two molecules so that the communication can start. Bacteria "B" produces another particle if and only if the two molecules that bacteria "A" released are present. The same behavior is observed in bacteria "C" with the molecules coming from "B". This example shows how bacterial communities suit the objective of swarm intelligence developments. Moreover, the possibility of engineer bacterial networks is extraordinarily relevant for medical and biological purposes.

4. CONCLUSION

This paper presents a promising direction for future developments in swarm intelligence and biological research. Two suggestions are made in this work from the computer science point of view. The first one is related to make profit of the advantages that the bacterial communication mechanism presents in order to broaden the objectives of swarm intelligence algorithms. The second one concerns the parallel and conditional work between SI algorithms based on bacteria and the work with real bacteria in the laboratory. Obviously we cannot design ants or bees but we can design bacteria in-vivo. The achievements of bacterial based SI systems can be used in the laboratory so that researchers can take advantage of the incredible computational power of real bacteria.

REFERENCES

[1] Marco Dorigo. "The Ant Colony Optimization Metaheruristic: Algorithms, Applications and Advances". *Methaeuristics Handbook*, 2001

[2] Paul G. Flikkema and Jeffrey G. Leid. "Bacterial Communities: A Microbiological Model for Swarm Intelligence". *IEEE 0-7803-8916-6*, 2005.

[3] Dong Hwa Kim, Ajith Abraham and Jae Hoon Cho. "A Hybrid Genetic Algorithm and Bacterial Foraging Approach for Global Optimization". *Information Sciences 177 3918-3937- Science Direct, Elsevier*, 2007.

[4] E. Bonabeau, M. Dorigo and G. Theraulaz. "Swarm Intelligence: From Natural to Artificial Systems". *New York, NY: Oxford University Press*, 1999

[5] M. Dorigo. Ant Colony System. URL: http://iridia.ulb.ac.be/dorigo/ACO/ACO.html

[6] D. Karaboga, "An Idea Based On Honey Bee Swarm For Numerical Optimization". *Technical Report-TR06*, Erciyes University, Engineering Faculty, Computer Engineering Department 2005.

[7] D. Karaboga, B. Basturk Akay and C. Ozturk. "Artificial Bee Colony (ABC) Optimization Algorithm for Training Feed-Forward Neural Networks", *LNCS: Modeling Decisions for Artificial intelligence, Vol: 4617/2007* pp:318-319, Springer-Verlag, 2007.

[8] A. Eberhard, AL. Burlingame, C. Eberhard, GL. Kenyon, KH. Nealson and NJ. Oppenheimer. "Structural identification of autoinducer of Photobacterium fischeri".*Biochemistry 20 2444-2449*, 1981

[9] C. Fuqua and A. Eberhard. "Signal generation in autoinduction systems: synthesis of acylated homoserine lactones by LuxI type proteins.*Cell-Cell Signaling in Bacteria. Dunny G and Winans SC, eds. pp 211-230 ASM Press, Washington DC*, 1999.

[10] S. Alberghini, E. Polone, V. Corich, M. Carlot, F. Seno, A. Trovato and A. Squartini. "Consequences of relative cellular positioning on quorum sensing and bacterial cell to cell communication" *FEMS Microbiol Lett 292. pp 149-161* 2009.

[11] JW. Costerton, Z. Lewandowski, DE. Caldwell, DR. Korber and HM. Lappin-Scott. "Microbial Biofilms",*Annu. Rev. Microbiol 49:711-745*

[12] JW. Costerton, PS. Stewart, EP. Greenberg. "Bacterial biofilms: a common caus of persistent infections", *Science 284:1318-1322*

[13] Alok Singh, "An Artificial Bee Colony Algorithm for the Leaf-Constrained Minimum Spanning tree problem" *Applied Soft Computing, Volume 9, Issue 2* pp 625-631, 2009.

[14] D. Karaboga, B. Akay, "Effect of Region Scaling on the Initialization of Particle Swarm Optimization, Differential Evolution and Artificial Bee Colony Algorithms on Multimodal High Dimensional Problems", *International Conference on Multivariate Statistical Modelling and High Dimensional Data Mining*, Erciyes University, Kayseri, Turkey.19-23 June 2008.

[15] JB. Anderson, A. Heydorn, L. Eberl, O. Geisenberger, B. Bak Christensen, S. Molin and M. Givskov. "GFP-Based N-acyl Homoserine Lactone Sensor systems for Detection of Bacterial Communication.*Appl Environ Microb 67* pp 575-585. 2001.

[16] P. Stewart, "Diffusion in biofilms", *J Bacteriol 185*, 1485-149, 2003.

[17] PS. Stewart, "A Review of experimental measurements of effective diffusive permeabilities and effective diffusion coefficients in biofilms". *Biotechnol Bioeng 59*, pp 261-272, 1998.

[18] Gregory Batt, Boyan Yordanov, Ron Weiss and Calin Belta, "Robustness analysis and tuning of synthetic gene networks", *Bioinformatics, System Biology Vol 23, no 18* pp 2415-2422. Oxford University Press, 2007.