Preface

BACKGROUND

The visible side of nature has always been a source of inspiration not only for poets, artists, sages, philosophers, but also for remarkable scientists and researchers during the history of mankind. Remember in this context, for example, the works of Leonardo da Vinci, e.g. his *Codex on the Flight of Birds* which can be considered as an early study on the nature of flight and as providing suggestions for designing flying machines.

The last decades have witnessed a tremendous progress in science and technology that allowed a better visualization and understanding of the profound biological and biochemical building blocks of life. Consequently, the invisible side of nature has become a source of knowledge, action, and inspiration as well. New powerful visualization techniques (such as cryo-electron tomography, or the nuclear magnetic resonance) allowed us to delve into the intricate mechanisms of life and understand how a cell works. Cell biologists have benefitted the most from this unprecedented flow of data which still waits to be deciphered and transformed into valuable information and actionable knowledge.

We now know that all cells store their hereditary information using the same linear chemical code of DNA. Due to technological advances of the sequencing machines we know the complete genome sequences for humans and many other species (but still only a minor part of the huge number of the estimated 10 million living species on Earth). We know that a mechanism of templated polymerization allows the cells to replicate their hereditary information. The DNA is made of simple subunits, called nucleotides and a DNA strand can be seen as a string over an alphabet with 4 letters (A, T, C, G). This hereditary information is transcribed into strings over the RNA alphabet (A, U, C, G) and then expressed into proteins, the primordial agents of the biochemical activities. With some minor exceptions, the rules governing this translation into proteins (the genetic code) are the same for every living form.

The cell can be considered as a very complex dynamic biochemical system, with thousands of chemical reactions taking place simultaneously. The vast majority of cell reactions can take place only in the presence of specialized proteins (enzymes). The proteins also play a variety of other functional and structural roles. Each and every cell is separated from the outer environment by the plasma membrane. This membrane acts as a barrier whose function is to maintain different concentrations of solutes in the cytosol as compared to the internal compartments and to the outer environment (extracellular fluid). There are specialized proteins that allow the passage of small molecules across the cell's membrane, proteins that are embedded in the membrane. These proteins are transporters (proteins with moving parts) and channels (forming hydrophilic pores). The importance of membranes as separators of chemical reactions is evident in the presence of several intracellular compartments (or organelles) with separate enzymes and molecules moving between them.

The field of bio-inspired computation has a long history marked by famous pioneers, such as Walter Pitts, Warren McCulloch, Alan Turing, Norbert Wiener, John von Neumann. In his unfinished book, *The Computer and the Brain* (first published in 1958), von Neumann presented his view on the analogies and difference between brains and computers and gave some directions for further research. Natural computing is now a very active research area that is concerned with the observation and study of computing-like processes taking place in nature and with the implementation of algorithms, programs and technical systems inspired by these natural processes. We can mention here a plethora of examples of systems and algorithms: cellular automata, evolutionary algorithms, neural networks, quantum computing, DNA computing, artificial immune systems, systolic arrays, artificial tissues, artificial life, synthetic genomes, particle swarm optimization, ant colony optimization, artificial bee colony algorithm, bacteria foraging, leaping frog algorithm, cuckoo search, bat algorithm, firefly algorithm, flower pollination algorithm, artificial plant optimization algorithm, bird flocking, fish schooling, protein memories, etc. These "many facets of natural computing" are investigated in a review by Kari and Rozenberg (2008) that takes the reader from the basic paradigms of cellular automata, artificial neuron model, and evolutionary computation, to the more recent concepts of swarm intelligence, artificial immune systems, and membrane computing.

A better understanding of the cell architecture and functioning has led to the development of new computing models. For example, DNA computing has emerged since 1994 with the seminal paper of Adleman as a fruitful and exciting new research field at the intersection of biology, computer science, mathematics, and engineering. Since then, various models of molecular computation have been proposed (filtering models, splicing models, constructive models, membrane models). Of these models, this book is focused on membrane computing which has been introduced in 1998 by the Romanian mathematician Gheorghe Păun. He proposed a parallel and distributed computing model starting from the study of cellular membranes. In 2003, the Institute for Scientific Information (ISI) considered membrane computing as an “emerging research area of computer science”.

Membrane computing has attracted at the beginning mainly mathematicians and theoretical computer scientists. Lately, scientists from other disciplines have become interested in the use of this computing model, and we can mention here economists, applied computer scientists, engineers, and robotics specialists. Hundreds of researchers from more than 30 countries have been involved both in theoretical studies and in proposing and developing far reaching applications. There have been reported successful applications in a wide range of areas, such as linguistics, modelling of biological processes (systems and synthetic biology), computer graphics, optimization, economics, and multiple engineering areas. More than 2500 publications and 100 Ph.D. theses regarding membrane computing have been published by authors around the world since the introduction of the original model by Păun. In 2016, the International Membrane Computing Society has been founded with the goal of promoting research and cooperation within the vibrant membrane computing community.

Recently, a great interest has been shown in controlling mobile robots using membrane computing based approaches, a research area that has been sparked by the research done at the *Natural Computing and Robotics Laboratory* of the *Politehnica University of Bucharest*.

Robotics is a fast developing field with far reaching implications in every domain of our life. Much more, as the recent developments in the field show, robotics is a driving and integrative technology that will ultimately find a place in everyday life.

A reference document for the robotics professionals is the *Robotics 2020 Multi-annual Roadmap* where a detailed presentation of applications, abilities, and technologies for robotic systems is given. The application areas for robotic systems are very diverse: manufacturing, healthcare, agriculture, civil domain, commercial domain, logistics and transportation, consumer robots. Each of these broad areas can be further detailed on further sub-domains. For example, the consumer robots can be further classified into four sub-domains: domestic appliances, entertainment, education, and assisted living, each with their own objectives and constraints. For example, robots co-existing with children in domestic and public environments are expected to behave as safe, fun, and reliable companions and tutors, and be also capable of engaging in playful and meaningful interaction.

The robotic systems can possess (at different levels) various abilities, such as: adaptability, cognitive ability, configurability, decisional autonomy, dependability, interaction ability, manipulation ability, motion ability and perception ability.

Robotic technologies are grouped by purpose into four clusters, according to the same roadmap mentioned above:

1. Systems Development (systems engineering, system design, system integration): better systems and tools;
2. Human Robot Interaction (human machine interface, safety, human robot collaboration): better interaction;
3. Mechatronics (actuators, control, sensors, communication): making better machines; perception;
4. Navigation and Cognition (interpretation, sensing, motion planning, mapping, localization, natural interaction, cognitive architectures, action planning): better action and awareness.

Multi-robot systems are groups of homogeneous or/and heterogeneous robots that act in a shared environment in order to achieve tasks collectively when the given task is too complicated or impossible to achieve for a single robot, when the task is by its nature distributed, when we want the task to be fulfilled quicker, or when robustness is a key factor (the failure of a single robot would not make the task not achievable when there are multiple, redundant, robots in the group). The control in multi-robot systems is implemented in a centralized or decentralized manner. Multi-robot systems have found their way in a large number of applications, such as exploration and surveillance, search and rescue, warehouse management and operations planning (Kiva robots for the Amazon warehouses), robot toys and intelligent transportation systems. Swarm robotics is an area of multi-robot systems based on the principles of local interaction (possibly mediated by the environment) between simple robots that ultimately leads to the emergence of a complex macroscopic behavior. Swarms of flying robots can be used in disaster areas to create communication areas or in conflict areas to monitor adverse actions, while for example swarms of robotic fish with appropriate chemical sensors can be used for searching and monitoring contaminants and pollutants.

Networked robotics refers to the system of systems approach of robots, sensors, computers and users interconnected via network communication technologies. Robotic swarms are large multi-robot systems (typically homogeneous in what regards the morphology, size, behavior, cognition) based on inspiration from natural societies (ants, birds, bees) and on the principles of swarm intelligence: decentralized control and simple local control rules (interaction) between simple agents. They are mostly used as demonstrators of simple yet powerful interaction mechanisms that lead to interesting global behaviors that mimic the abilities of large colonies of simple insects in tasks like: search, foraging, grazing, harvesting, deployment, coverage, transportation, exploration, pursuit, predator-prey, etc. In the same time, examples of effective application of swarm robots have started to appear in the mainstream, such as the swarms of flying robots for search in disaster areas, inspection and maintenance with swarms of micro aerial robots, ocean monitoring, swarms of robotic fish.

Bio-inspired techniques have found numerous applications in robot design and control. Various innovative concepts and technologies have been designed and tested such as: robots with flapping wings, insect-like eyes, very sensitive robotic skins, artificial muscles, fish robots with chemical sensors, locust-like jumping mechanisms, soft actuators and sensors, conformable robots, climbing robots, helical swimming robots, robots with bio-inspired spine mechanisms, (high speed) running robots, robots with compliant pockets, flexible and transient electronics.

In the area of planning, optimization and control, there have been reported bio-inspired applications in the gait planning for biped robots, optimization of robot work cell layout, robust adaptive control of robot manipulators, robust control of robot arm-and-hand system, autonomous landing for flying robots, learning motion trajectories, fuzzy and neural controllers for mobile robots, multi robot area exploration, etc.

CONTENTS

We propose a systematic and detailed treatment of the use of membrane computing for robot control in a book which is easy to follow and clearly structured. We provide the fundamental concepts of membrane computing and mobile robotics and then we continue with methods for designing and testing membrane computing based controllers for single mobile robots as well as for swarms of mobile robots. We also approach the overlooked issue of robot swarms security using a membrane computing approach. Overall, our book provides a ready to use conceptual framework for how to integrate membrane computing in mobile robotics in addition to other modelling and simulation tools and computational approaches. There are many simulation examples, and part of the included experiments are validated on open-source, low cost mobile robots (*Kilobot*).

The dedicated webpage (http://membranecomputing.net/IGIBook/) is an additional source of information where source code, input files, user manuals, and demonstration videos can be found.

We now describe in detail the structure of this book.

Chapter 1 gives an overview of swarm robotics. First, we position this area in the context of the fast developing field of robotics and secondly, we present the fundamental concepts of decentralized control, local interaction, stigmergy, and emerging intelligence. Examples of typical robots used in swarm robotics experiments are given together with examples of robot simulators.

In Chapter 2 we introduce the fundamental concepts of membrane computing and define the basic P systems models that are considered relevant – at the time of this writing – to the robotics specialists. Among these are the numerical P systems, enzymatic numerical P systems, P colonies, XP colonies, and P swarms. Detailed examples will help the reader to understand how these systems work. We close this chapter with an extended analogy between membrane computing and swarm robotics that lies at the basis of our work reported in Chapter 4.

Chapter 3 is concerned with an overview of the software simulators for membrane computing. First we present some of the simulation approaches and software described in the literature, and then we continue with a more detailed presentation of the software simulators we have designed at the *Natural Computing and Robotics Laboratory* from the *Politehnica University of Bucharest*: *SNUPS* (for simulating standard and enzymatic numerical P systems), *Lulu* (an open-source simulator for P colonies and P swarms) and *PeP* (an open-source simulator for standard numerical P systems and their variants).

The core of this book is represented by Chapter 4. There we will describe in a very detailed manner how to use basic membrane computing models for controlling single and multiple robots, both simulated and real-world robots. Source code and state diagrams will intermediate a better understanding of the basic principles of membrane computing based control of robots.

In Chapter 5 we conclude this book by giving an overview of how to use membrane computing in robot control. We indicate which membrane computing models can be used to solve various problems in robotics, such as localization, obstacle avoidance, dispersion etc. We end with providing some research directions that could lead to the development of this field.

TARGET AUDIENCE

We hope that our book will be welcomed by a wide range of readers interested in understanding the fundamentals of membrane computing, and of controlling mobile robots using bioinspired approaches based on membrane computing models.

We will gladly welcome any comments, suggestions, and proposals for cooperation.

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