N. Correll. Cells and Robots --- Modeling and Control of Large-Size Agent Populations by Dejan Lj. Milutinovic and Pedro Lima. IEEE Control Systems Magazine, Volume 28, Number 5, pages 140-141, October 2008.

Cells and Robots – Modeling and Control of Large-Size Agent Populations by Dejan Lj. Milutinović and Pedro Lima, Springer Verlag, 2007, 124 pages, ISBN-10 3-540-71981-4, $109. Reviewed by *Nikolaus Correll.*

The relation between robots and cells suggested by the book title might be surprising as it is probably not apparent at first sight. Thinking about this more closely, however, the following facts come to mind. Single cell organisms like bacteria explore their environment by gradient descent towards nutrition sources or magnetic fields and communicate with each other via inter-cellular channels. These mechanisms as well as collective natural phenomenon at the nano-scale such as the immune system have already inspired the design of algorithms and sub-systems for robot swarms. Where these capabilities might also lead us is well summarized by the title of H.C. Berg's - a world-expert on cell motility - keynote talk at the *Robotics: Science and Systems* Conference this year in Zurich "Motile Behavior of E. Coli, a Remarkable Robot" [1]. Moreover, the emerging field of synthetic biology aims at making the design of cells with specific properties an engineering discipline, and it is thus likely that future nano-robotic swarms will rely on a significant biological component for sensing and actuation.

For these reasons, models developed for collective cellular systems might be potentially applicable to robotic swarms and vice versa. In particular, a mathematical model of such systems might help us to formally understand the relation between individual and collective dynamics – a challenging question among multiple disciplines, whether considering the immune system or robotic swarms. Milutinović and Lima's book is a step forward towards the solution of this quest. The book introduces a hybrid [4] dynamical modeling framework for modeling both the discrete population dynamics as well as the distribution of the swarm in a continuous state space. This differs from previous work which aims at either modeling the non-spatial population dynamics of a swarm over discrete sets, i.e. the fraction of swarm members in a specific behavioral state (e.g., [2] for a difference equation model for a swarm-robotics case study), or modeling the distribution of the swarm in a continuous state space (e.g., [3] for differential equation models commonly used in virology and immunology). The authors assume that individual members of the swarm switch between the discrete states probabilistically. They further assume that a vector field is associated with each discrete state and that this vector field is responsible for the temporal evolution of the distribution in the continuous space. The authors then develop a system of partial differential equations (PDEs) that describe the change of the continuous distribution of each of the discrete states as a function of both the state transition probabilities between discrete states and the vector fields that affect the continuous state distributions. This approach is illustrated using two case studies: the distribution of T-cell expression levels in the immune system, and the spatial distribution of a swarm of robots. Here, both T-cells and robots can be in one of multiple discrete behavioral states, whereas the continuous state distribution describes the expression level of the T-cell population or the location of the robots.

After introducing the reader briefly to the analogy between an individual robot and a cell in terms of sensors and actuators in Chapter 1 and the immune system and T-Cell receptor dynamics in Chapter 2, Chapter 3 introduces the hybrid automata approach that is used for modeling the individual swarm member throughout the book. Chapter 4 then describes the relation between the hybrid automaton that describes the individual dynamics and the macroscopic dynamics. This relation is captured by the PDE model described above. The developed method is then applied to the T-cell expression case study in Chapter 5. Noteworthy contributions of this chapter are the validation of the PDE approach using experimental data, as well as the comparison of the proposed PDE model that explicitly describes the distribution of T-cell expression dynamics with commonly used ordinary differential equation (ODE) models. ODE models are limited to describing average quantities, whereas the proposed PDE system also describes the distributions of these quantities. Chapter 6 then explores populations with heterogeneous parameters and extends the modeling framework by explicitly modeling the resulting parameter uncertainty in the PDE system.

The primary purpose of modeling the T-cell population in the immune system is a better system understanding and prediction of laboratory observations. For fully engineered systems, such as a robot swarm, models can serve an additional purpose: they can be used for the design of the individual agent. Using methods from optimal control (in particular the minimum principle for PDEs), Chapter 7 then shows how the *individual* state transitions need to be tuned in an open-loop control scheme to achieve a desired distribution in the continuous state space. The conclusion in Chapter 8 is followed by appendices that detail experimental and analysis methods relevant for the T-cell experiments (Appendix A-C). Finally, Appendix D reviews the minimum principle for PDEs.

This book addresses the advanced researcher or graduate student who is interested in a probabilistic perspective on modeling of large-scale distributed systems. Appreciating the book to its full extent, however, requires a solid background in partial differential equations and optimal control theory. Similarly, following the reasoning of the author is often difficult – depending on the reader's background - when biological or robotic knowledge is required to follow the intuition behind the presented models. Although Chapter 1 and Chapter 2 provide a brief overview of robotic sensors and actuators and the relevant aspects of T-cell dynamics, respectively, I personally needed the intuition provided by the robotics example in Chapter 7 to fully understand the PDE modeling formalism, which in turn helped me to understand the immune system case study. Fortunately, each chapter in Milutinović and Lima's book is self-contained, which caters to the reader who wants to read chapters selectively.

One might argue that the case studies brought forward by the authors are very specific and that in particular the robotic case study might be of limited application and lacks validation at a lower modeling abstraction level. Nevertheless, this book elaborates on two important points. First, the authors introduce an extremely compact model that describes the evolution of the probabilistic state distribution of a multi-agent system with discrete and continuous states to the biologist and the robotics community. Second, by controlling average quantities and their distributions rather than deterministically controlling the individual agent the authors advance the state of the art in modeling of large-scale distributed systems whose agents are of limited capabilities and subject to sensor and actuator noise. In summary, I recommend this book to anyone who is interested in a probabilistic perspective on modeling of large-scale distributed systems – an area that definitely deserves more attention.

References

[1] http://roboticsconference.org/

[2] A. Martinoli, K. Easton, and W. Agassounon. Modeling Swarm-Robotic Systems: A Case Study in Collaborative Distributed Manipulation. Int. Journal of Robotics Research, 23 (2004), pp. 415-436.

[3] M. A. Nowak and R. M. May. Virus Dynamics: Mathematical Principles of Immunology and Virology, Oxford University Press, 2000.

[4] A. J. van der Schaft and J. M. Schumacher. An Introduction to Hybrid Dynamical Systems, Springer-Verlag, 2000.

Author-Bio

Dr. Nikolaus Correll is a post-doctoral fellow at the Distributed Robotics Laboratory, Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology. Nikolaus earned a Master's in Electrical Engineering from the Swiss Federal Institute of Technology (ETH) in Zurich in 2003, and a PhD in Computer Science from the Ecole Polytechnique Federale Lausanne (EPFL) in 2007. Nikolaus' research interests are large-scale distributed robotic systems, mixed animal-robot societies and monitoring of collective systems. Nikolaus is technical program co-chair for the nano-robotics track at Nano-Nets 2008 in Boston and serves as reviewer for several international robotics journals and conference proceedings. *nikolaus@csail.mit.edu*