Report from Dagstuhl Seminar 16271

Algorithmic Foundations of Programmable Matter

Edited by

Sándor Fekete[1], Andréa W. Richa[2], Kay Römer[3], and Christian Scheideler[4]

1 **TU Braunschweig, DE,** s.fekete@tu-bs.de
2 **Arizona State University – Tempe, US,** aricha@asu.edu
3 **TU Graz, AT,** roemer@tugraz.at
4 **Universität Paderborn, DE,** scheideler@upb.de

Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 16271 "Algorithmic Foundations of Programmable Matter", a new and emerging field that combines theoretical work on algorithms with a wide spectrum of practical applications that reach all the way from small-scale embedded systems to cyber-physical structures at nano-scale.

The aim of the Dagstuhl seminar was to bring together researchers from the algorithms community with selected experts from robotics and distributed systems in order to set a solid base for the development of models, technical solutions, and algorithms that can control programmable matter. Both communities benefited from such a meeting for the following reasons:

- Meeting experts from other fields provided additional insights, challenges and focus when considering work on programmable matter.
- Interacting with colleagues in a close and social manner gave many starting points for continuing collaboration.
- Getting together in a strong, large and enthusiastic group provided the opportunity to plan a number of followup activities.

In the following, we provide details and activities of this successful week.

Seminar July 3–8, 2016 – http://www.dagstuhl.de/16271

1998 ACM Subject Classification C.2.4 [Computer Communications Networks] Distributed Systems, F.1.2 [Computation by Abstract Devices] Modes of Computation, F.2.2 [Analysis of Algorithms and Problem Complexity] Nonnumerical Algorithms and Problems, I.2.9 [Artificial Intelligence] Robotics, I.2.9 [Artificial Intelligence] Robotics – Modular Reconfigurable Robots, I.6 [Simulation and Modeling] General

Keywords and phrases distributed algorithms, distributed systems, programmable matter, robotics, self-organization

Digital Object Identifier 10.4230/DagRep.6.7.1

Edited in cooperation with Thim Strothmann

Algorithmic Foundations of Programmable Matter, *Dagstuhl Reports*, Vol. 6, Issue 7, pp. 1–14
Editors: Sándor Fekete, Andréa W. Richa, Kay Römer, and Christian Scheideler
Dagstuhl Reports
Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

1 Executive Summary

Sándor Fekete
Andréa W. Richa
Kay Römer
Christian Scheideler

Programmable matter refers to a substance that has the ability to change its physical properties (shape, density, moduli, conductivity, optical properties, etc.) in a programmable fashion, based upon user input or autonomous sensing. The potential applications are endless, e.g., smart materials, autonomous monitoring and repair, or minimal invasive surgery. Thus, there is a high relevance of this topic to industry and society in general, and much research has been invested in the past decade to fabricate programmable matter. However, fabrication is only part of the story: without a proper understanding of how to program that matter, complex tasks such as minimal invasive surgery will be out of reach. Unfortunately, only very few people in the algorithms community have worked on programmable matter so far, so programmable matter has not received the attention it deserves given the importance of that topic.

The Dagstuhl seminar "Algorithmic Foundations of Programmable Matter" aimed at resolving that problem by getting together a critical mass of people from algorithms with a selection of experts from distributed systems and robotics in order to discuss and develop models, algorithms, and technical solutions for programmable matter.

The aim of the proposed seminar was to bring together researchers from the algorithms community with selected experts from robotics and distributed systems in order to set a solid base for the development of models, technical solutions, and algorithms that can control programmable matter. The overall mix worked quite well: researchers from the more practical side (such as Julien Bourgeois, Nikolaus Correll, Ted Pavlic, Kay Römer, among others) interacted well with participants from the theoretical side (e.g., Jennifer Welch, Andrea Richa, Christian Scheideler, Sándor Fekete, and many others). Particularly interesting to see were well-developed but still expanding areas, such as tile self-assembly that already combines theory and practice (with visible and well-connected scientists such as Damien Woods, Matt Patitz, David Doty, Andrew Winslow, Robert Schweller) or multi-robot systems (Julien Bourgeois, Nikolaus Correll, Matteo Lasagni, André Naz, Benoît Piranda, Kay Römer).

The seminar program started with a set of four tutorial talks given by representatives from the different sets of participants to establish a common ground for discussion. From the robotics and distributed system side, Nikolaus Correll and Julien Bourgeois gave tutorials on smart programmable materials and on the claytronics programmable matter framework respectively. From the bioengineering side, Ted Pavlic gave a tutorial on natural systems that may inspire programmable matter. From the algorithmic side, Jacob Hendricks gave a tutorial on algorithmic self-assembly. In the mornings of the remaining four days, selected participants offered shorter presentations with a special focus on experience from the past work and especially also open problems and challenges. Two of the afternoons were devoted to discussions in breakout groups. Four breakout groups were formed, each with less than 10 participants to allow for intense interaction. Inspired by a classification of research questions in biology into "why?" and "how?" questions presented in Ted Pavlic's tutorial, the first breakout session was devoted to the "why?" questions underpinning programmable matter, especially also appropriate models of programmable matter systems (both biological or engineered) suitable for algorithmic research. The second breakout sessions towards the end of the seminar was devoted to a set of specific questions given by the organizers that resulted from the discussions among the participants, they included both research questions and organizational questions (e.g., how to proceed after the Dagstuhl seminar). After each of the two breakout sessions, one participant of each of the four breakout groups reported back the main findings of the discussions to the plenum, leading to further discussion among all participants. One of the afternoons was devoted to a hike to a nearby village, where the participants also visited a small museum devoted to programmable mechanical musical devices.

The seminar was an overwhelming success. In particular, bringing together participants from a number of different but partially overlapping areas, in order to exchange problems and challenges on a newly developing field turned out to be excellent for the setting of Dagstuhl – and the opportunities provided at Dagstuhl are perfect for starting a new community.

Participants were enthusiastic on a number of different levels:

- Meeting experts from other fields provided additional insights, challenges and focus when considering work on programmable matter.
- Interacting with colleagues in a close and social manner gave many starting points for continuing collaboration.
- Getting together in a strong, large and enthusiastic group provided the opportunity to plan a number of followup activities.

The latter include connecting participants via a mailing list, the planning and writing of survey articles in highly visible publication outlets, and a starting point for specific scientific workshops and conferences.

Participants were highly enthusiastic about the possibility of another Dagstuhl workshop in the future; organizers will keep the ball rolling on this – most likely, for an application in the coming spring, so that some more details can be worked out in the meantime.

2 Table of Contents

3 Overview of Talks

3.1 Claytronics: an Instance of Programmable Matter

Julien Bourgeois (FEMTO-ST Institute – Montbéliard, FR)

Joint work of Julien Bourgeois, Seth Copen Goldstein
Main reference J. Bourgeois, S. Copen Goldstein, "Distributed Intelligent MEMS: Progresses and Perspectives", IEEE Systems Journal, 9(3):1057–106, 2015.
URL http://dx.doi.org/10.1109/JSYST.2013.2281124

Programmable matter (PM) has different meanings but they can be sorted depending on four properties: Evolutivity, Programmability, Autonomy and Interactivity. In my talk, I will present the Claytronics project which is an instance of PM, evolutive, programmable, autonmous and interactive. In Claytronics, PM is defined as a huge modular self-reconfigurable robot. To manage the complexity of this kind of environment, we propose a complete environment including programmable hardware, a programming langage, a compiler, a simulator, a debugger and distributed algorithms.

3.2 A Markov Chain Algorithm for Compression in Self-Organizing Particle Systems

Sarah Cannon (Georgia Institute of Technology – Atlanta, US)

Joint work of Sarah Cannon, Joshua J. Daymude, Dana Randall, Andréa W. Richa
Main reference S. Cannon, J. J. Daymude, D. Randall, A. W. Richa, "A Markov Chain Algorithm for Compression in Self-Organizing Particle Systems", in Proc. of the 2016 ACM Symp. on Principles of Distributed Computing (PODC'16), pp. 279–288, ACM, 2016.
URL http://dx.doi.org/10.1145/2933057.2933107

One can model programmable matter as a collection of simple computational elements (called particles) with limited (constant-size) memory that self-organize to solve systemwide problems of movement, configuration, and coordination. In recent work with Joshua J. Daymude, Andrea Richa, and Dana Randall, we focused on the compression problem, in which the particle system gathers as tightly together as possible, as in a sphere or its equivalent in the presence of some underlying geometry. More specifically, we presented a fully distributed, local, and asynchronous algorithm that leads the system to converge to a configuration with small perimeter. Our Markov chain based algorithm solves the compression problem under the geometric amoebot model, for particle systems that begin in a connected configuration with no holes. I will give a brief overview of Markov chains, describe our Markov chain and why it achieves particle compression, and show how it leads to a fully distributed, local, and asynchronous protocol each particle can run independently. Furthermore, I'll discuss how Markov chains might be amenable for use in other programmable matter contexts

3.3 Algorithm design for swarm robotics and smart materials

Nikolaus Correll (University of Colorado – Boulder, US)

Main reference M. A. McEvoy, N. Correll, "Materials that couple sensing, actuation, computation, and communication", Science, 347(6228), p. 1261689, 2015.
URL http://dx.doi.org/10.1126/science.1261689

"Programmable Matter" is a conjunction of a discrete program and continuous matter. Where the line between the two needs to be drawn is currently unclear. One approach is to abstract matter to the point where it can be treated exclusively by discrete models. Another approach is to think about individual elements becoming so small that they are captured by continuous physics such as fluid dynamics. In this tutorial, I argue for and explain a hybrid automata model that consists of a discrete network of computers, which can sense and actuate on a continuous material that the network is integrated in. Here, communication not only happens through the network, but also in the material itself via sensor/actuator coupling. I illustrate this approach using a series of "robotic materials" including a sensing skin, a shape-changing beam, and a modular wall that can recognize gestures. These systems demonstrate a number of algorithmic challenges ranging from networking, distributed control and optimization, and programming. At the same time, each instance illustrates that material properties strongly influence algorithmic design and vice versa.

3.4 Dynamic Networks of Computationally Challenged Devices: the Passive Case

Yuval Emek (Technion – Haifa, IL)

Joint work of Yuval Emek, Jara Uitto, Roger, Wattenhofer
Main reference Y. Emek, R. Wattenhofer, "Stone age distributed computing", in Proc. of the 2013 ACM Symp. on Principles of Distributed Computing (PODC'13), pp. 137–146, ACM, 2013.
URL http://dx.doi.org/10.1145/2484239.2484244

Motivated by applications in biology and nano-technology, the trend of applying the "distributed computing approach" to networks of message passing devices with weak computation (as well as communication) capabilities is gaining momentum. So far, most of the advances have been made under the assumption that (1) the network is static; or (2) the dynamic behavior of the network is dictated by devices that can actively control their own motion. In this talk, I'd like to discuss some research questions related to such networks that undergo dynamic (adversarial) topology changes in which the devices only play a passive role.

3.5 Algorithms for robot navigation: From optimizing individual robots to particle swarms

Sándor Fekete (TU Braunschweig, DE)

Joint work of Aaron Becker, Erik D. Demaine, Maximilian Ernestus, Sándor Fekete, Michael Hemmer, Alexander Kröller, Dominik Krupke, SeoungKyou Lee, James McLurkin, Rose Morris-Wright, Christiane Schmidt, S. H. Mohtasham

Planning and optimizing the motion of one or several robots poses a wide range of problems. How can we coordinate a group of weak robots to explore an unknown environment? How can we ensure that a swarm of very simple robots with local capabilities can deal with conflicting global requirements? And how can a particle swarm perform complex operations? We will demonstrate how an appropriate spectrum of algorithmic methods in combination with geometry can be used to achieve progress on all of these challenges.

3.6 The Amoebot Model

Robert Gmyr (Universität Paderborn, DE)

Joint work of Zahra Derakhshandeh, Robert Gmyr, Andréa W. Richa, Christian Scheideler, Thim Strothmann
Main reference Z. Derakhshandeh, R. Gmyr, A. W. Richa, C. Scheideler, T. Strothmann, "Universal Shape Formation for Programmable Matter", in Proc. of the 28th ACM Symposium on Parallelism in Algorithms and Architectures (SPAA'16), pp. 289–299, ACM, 2016.
URL http://dx.doi.org/10.1145/2935764.2935784

We envision programmable matter consisting of systems of computationally limited devices that are able to self-organize in order to achieve a desired collective goal without the need for central control or external intervention. Our formal investigation of programmable matter is based on the Amoebot model. In this talk, I will give a brief introduction to this model. Furthermore, I will give an overview of our work on three central problems, namely shape formation, coating, and leader election.

3.7 Dances with Plants: Robot-supported Programmable Living Matter

Heiko Hamann (Universität Paderborn, DE)

Joint work of Mostafa Wahby, Mohammad Divband Soorati, Heiko Hamann
Main reference H. Hamann, M. Wahby, T. Schmickl, P. Zahadat, D. Hofstadler, K. Støy, S. Risi, A. Faina, F. Veenstra, S. Kernbach, I. Kuksin, O. Kernbach, P. Ayres, P. Wojtaszek, "*flora robotica* – Mixed Societies of Symbiotic Robot-Plant Bio-Hybrids", in Proc. of the IEEE Symp. on Computational Intelligence (SSCI'15), pp. 1102–1109, IEEE, 2015.
URL http://dx.doi.org/10.1109/SSCI.2015.158

Besides standard self-reconfiguring modular robotics and self-assembly, robots can also be mixed with other components to form heterogeneous systems. For example, combining natural plants and distributed robot systems offers new approaches to programmable matter. Instead of applying methods of synthetic biology, the idea here is to make use of natural plant behaviors to control them. A second example is self-organized swarm construction of possibly actuated structures. These approaches offer unique advantages, such as growth of additional material for free, environmental safety, and simplicity, despite their limitations in flexibility concerning possible structures and potential for reconfigurations.

3.8 Introduction to Modeling Algorithmic Self-Assembling Systems

Jacob Hendricks (University of Wisconsin – River Falls, US)

This talk introduces theoretical tile based models of self-assembly. We first give the definition of Winfree's abstract Tile Assembly Model (aTAM) that was developed to study DNA based molecular building blocks. This talk proceeds with examples of specific tile assembly systems such as binary counters and Turing machine simulators as these demonstrate the possibility of algorithmic self-assembly. Then we discuss a few specific topics in the field. These topics include non-cooperative self-assembly, various models of self-assembly, common benchmarks for determining the capabilities and limitations of models, simulation as a means of comparing models, and finally, the notion of intrinsic universality. Topics have been selected to provide a bird's-eye view of a theoretician's considerations about modelling self-assembling systems using tile assembly models.

3.9 Advantages, Limitations, Challenges of Tendon-Driven Programmable Chains

Matteo Lasagni (TU Graz, AT)

Joint work of Matteo Lasagni, Kay Römer
Main reference M. Lasagni, K. Römer, "Force-guiding particle chains for shape-shifting displays", in Proc. of the 2014 IEEE/RSJ Int'l Conf. on Intelligent Robots and Systems (IROS'14), pp. 3912–3918, IEEE, 2014.
URL http://dx.doi.org/10.1109/IROS.2014.6943112

One of the first and most relevant questions when designing a shape-shifting material concerns particles' topology and hence their mobility. We can distinguish between detachable and non-detachable topologies. Detachable topologies allow particles to temporarily detach from the ensemble and freely migrate to different locations in order to obtain a shape-shift. In contrast, non-detachable topologies constrain particles to occupy a fixed location where only relative displacement between adjacent particles and/or particle deformation are allowed for shape-shift. Despite the fact that detachable topologies allow the formation of literally any shape, the complex architecture to enable particle migration, generally consisting of built-in actuators and latching mechanisms, raises costs and limits the scalability of the whole system, and causes inherent problems concerning particle power supply and communication. In our work, we demonstrate how a nondetachable topology can allow the formation of arbitrary complex shapes, thereby avoiding or at least limiting the above-mentioned problems. In particular, scalability and cost-effectiveness derive from the concatenation of semi-active particles without bulky built-in actuators and latches. Such particles, forming piecewise bendable chains, exploit remotely generated forces to self-actuate and hence to control the local curvature of the chain. Multiple chains can be combined to form a shape-shifting surface to support novel applications like 3D tangible displays or programmable molds. One major challenge concerns the actuation of the system. Without the support of optimal planning strategies able to schedule proper particle actuation, unbearable actuation forces might occur, for example, due to inconvenient leverage effects, with negative consequences for the system stability and integrity. Starting from the current configuration and aiming at the final target configuration, optimal planning techniques should explore the large set of possible *next configurations* where only a limited number of particles can actuate, and determine in which cases the intensity of the actuation forces is acceptable. The optimization problem involves not only a single independent chain, but applies simultaneously to all chains. Due to mechanical constraints, indeed, all chains need to actuate the same number of particles at each reconfiguration step. This calls for models able to predict the behavior of the whole system upon the application of specific control input in order to support optimal planning algorithms. Such models need to be sufficiently accurate to be consistent with reality but also computationally efficient to allow planning in reasonable time. An important question concerns the determination of an acceptable trade-off between these two aspects.

3.10 Programmable Matter for Dynamic Environments

Othon Michail (CTI – Rion, GR)

Joint work of Othon Michail, Paul G. Spirakis
Main reference O. Michail, P. G. Spirakis, "Terminating population protocols via some minimal global knowledge assumptions", J. Parallel Distrib. Comput., Vol. 81–82, pp. 1–10, 2015.
URL http://dx.doi.org/10.1016/j.jpdc.2015.02.005

We discuss two recent theoretical models of programmable matter operating in a dynamic environment. In the first model, all devices are finite automata, begin from the same initial state, execute the same protocol, and can only interact in pairs. The interactions are scheduled by a fair (or uniform random) scheduler, in the spirit of Population Protocols. When two devices interact, the protocol takes as input their states and the state of the connection between them (on/off) and updates all of them. Initially all connections are off. The goal of such protocols is to eventually construct a desired stable network, induced by the edges that are on. We present protocols and lower bounds for several basic network construction problems and also universality results. We next discuss a more applied version of this minimal and abstract model, enriched with geometric constraints, aiming at capturing some first physical restrictions in potential future programmable matter systems operating in dynamic environments.

3.11 Energy Harvesting in-vivo Nano-Robots in Caterpillar Swarm

Venkateswarlu Muni (Ben Gurion University of the Negev – Beer Sheva, IL)

Joint work of Shlomi Dolev, Sergey Frenkel, Venkateswarlu Muni, Michael Rosenblit, Ram Prasadh Narayanan

Biological collaborative systems behavior is fascinating, urging researchers to mimic their behavior through programmable matters. These matters constitute a particle system, wherein the particles bind with the neighboring particles to swarm and navigate. Caterpillar swarm inspired particle systems involves layered architecture with single to a predefined number of layers. Through this work, a coordinated layered particle system inspired by caterpillar swarm is discussed. We first propose a novel design for produce-able nano-particles that uses electrodes to harvest electricity from the blood serum, energy that can be later used for swarm inter and/or outer communication, moving, coordination, sensing and acting according to a given (instructing) program. The benefit of moving and acting in a swarm is demonstrated by a design of telescopic movement in pipes (e.g., blood vessels), wherein each layer uses the accumulated speed of all layers below and moves faster, thus, mimicking the faster motion of the caterpillar swarm.

3.12 Algorithmic design of complex 3D DNA origami structures

Pekka Orponen (Aalto University, FI)

Joint work of Erik Benson, Abdulmelik Mohammed, Johan Gardell, Sergej Masich, Eugen Czeizler, Pekka Orponen, Björn Högberg
Main reference E. Benson, A. Mohammed, J. Gardell, S. Masich, E. Czeizler, P. Orponen, B. Högberg, "DNA rendering of polyhedral meshes at the nanoscale", Nature, 523(7561):441–444, 2015.
URL http://dx.doi.org/10.1038/nature14586

In a recent work (Nature 523:441–444, July 2015), we described a general methodology and software pipeline for rendering 3D polyhedral mesh designs in DNA. In this talk, I will first summarise the basic idea of Paul Rothemund's DNA origami technique which also underlies our approach, and then proceed to discuss the graph-theoretic concepts and algorithmic ideas used in extending his technique from 2D patterns to 3D wireframe mesh structures. The reliability and generality of the approach is demonstrated by a number of electron microscopy images of synthesised nanostructures, including a 50-nm rendering of the widely-used Stanford Bunny model. I will also touch on the challenges of using DNA as a substrate for complex designs, and some related open questions.

3.13 Algorithmic Foundations of Biological Matter: Faster, Cheaper, and More Out of Control

Theodore P. Pavlic (Arizona State University – Tempe, US)

For at least the past 30 years, there has been much interest in developing programmable matter solutions that have been inspired by related phenomena in nature. Visionaries in computer science from the 1980's promised that such life-like phenomena would be possible, and yet the programmable matter of today still has limited capabilities. Rather than groups of relatively inexpensive agents grouping together to form an intelligent and flexible collective matter, the automation systems we have today combine relatively intelligent individual units together into rigid and often static structures that have no ability to adapt to the surrounding environment.

To make real progress in understanding the algorithms responsible for nature's success, computer scientists and engineers need to become familiar with the taxonomy of scientific questions in biology. The outputs of biological evolution are shaped not only by adaptive value (i.e., a design objective), but also by phylogeny (i.e., structures inherited from earlier forms), ontogeny (i.e., the process of constructing the object), and the actual mechanism of action that interacts with the environment. The former of these two pressures – adaptive value and phylogeny – are the subject of the "Why" questions of biology, and those questions must always be conditioned by the ancestral environment. The latter two of these pressures – ontogeny and mechanism – are the subject of the "How" questions of biology, and those questions must always be conditioned by the modern environment. This characterization of biological questions is not unlike the ways in which computer scientists consider algorithms and their implementations – in terms of design objectives, platforms, and algorithms that operate on those platforms. However, taking the objective–platform–algorithm approach alone with biological systems obscures details about evolution and ecology that are necessary for understanding how a biological system could possibly be working and whether it is really appropriate to take such an approach with an engineered system. Additionally, taking the effort to understand adaptive value of biological phenomena can provide interesting new motivations for problems that could be solved in engineered systems, albeit using totally different mechanisms.

When learning about programmable matter from biological systems, there are some biological model systems that are better matches than others. A flock of starlings produces beautiful patterns of so-called "active matter" in three-dimensional space. However, such patterns likely have no adaptive value themselves and are simply an epiphenomenon of behaviors which were shaped by individual-level selection to reduce predation risk. As a consequence, anyone trying to reverse engineer such patterns will likely not find much insight in biology. However, army ant bivouacs that are large, self-healing, self-regulating balls of ants in the middle of tropical forest may be a good model as this group-level phenomena is likely under selective pressure by natural selection. Similarly, army ant bridges that move and grow to some intermediate length have been shown to likely provide adaptive benefit to the group. So army ants seem to be a more fitting model for programmable matter than starling flocks. Ants, in general, are attractive targets as all ants evolved from an ancestor that was a solitary wasp; in essence, ants are distributed wasps, with individual workers taking on specialized tasks and aggregating together to form a colony that does what was once the work of a single individual. Although this description of ants is relatively general, there are a wide variety of different problem-solving methods that have evolved across ant taxa. Ants that use pheromone trails as external spatial shared memory apparently vary in how important those trails factor in their individual behaviors, and those variances allow some species of ants to be able to better track changes in the environment than other ants (at the cost of not being able to converge on group-level decisions as quickly). Ants that do not use pheromone trails make foraging and nest-site selection decisions much more slowly, but they have a notable ability to aggregate information from apparently irrational individuals that still produces rational outcomes at the group level. Laboratory tests that induce irrationality in individuals fail to generate the same irrationality in the groups. This kind of aggregation process would be valuable in the development of programmable matter that gathers information from its environment and processes it in a decentralized manner.

Beyond ants, there are other interesting systems that may be good models for programmable matter. One example is the slime mould, in particular the multinucleate slime mould. The multinucleate slime mould is a single cell, formed by the fusion of multiple cells, filled with nuclei and other organelles and surrounded by a flexible, growing membrane that gives the whole unit amoeboid characteristics. Through a decentralized process that dynamically induces pressure gradients around the amoeba-like macroscopic cell, it grows and shrinks and can perform a variety of interesting computations – like finding the shortest path through a maze, determining the right path through a Towers of Hanoi decision tree, and even re-allocating its biomass across different food sources with different mixtures of macronutrients so that the combined intake of those macronutrients is regulated to set levels. While both ants and slime moulds appear somewhat social, it is rare to think about the process of development as a decentralized, collective behavior or computation. However, developmental biologists have shown that cells are effectively executing programs based on internal state and local information from their microenvironment. Following these ideas, some have found ways to re-grow limbs on vertebrates and even induce multiple heads to grow on invertebrates. In the case of the example of the already regenerative planaria (flat worm), modifications induced by a temporary stimulus are latched into the tissue and remembered in all future generations. Those modifications can only be erased by applying drugs used in humans for suppressing memories. This suggests that the somatic tissue all around the body is itself a primitive neural network, capable of information processing and storage. Thus, biological tissue may be a very fitting model system for programmable matter.

In this talk, I will elaborate on these ideas and provide more examples of other biological systems that may provide useful insights when designing programmable matter that may someday finally realize a dream that has been deferred for decades.

3.14 VisibleSim:Your simulator for Programmable Matter

Benoît Piranda (FEMTO-ST Institute – Montbéliard, FR)

Joint work of Julien Bourgeois, Dominique Dhoutaut, André Naz, Benoît Piranda, Pierre Thalamy, Thadeu Tucci
Main reference D. Dhoutaut, B. Piranda, J. Bourgeois, “Efficient simulation of distributed sensing and control environments”, in Proc. of the 2013 IEEE Int’l Conf. on Internet of Things (iThings’13), pp. 452–459, IEEE, 2013.
URL http://dx.doi.org/10.1109/GreenCom-iThings-CPSCom.2013.93

VisibleSim is a 3D simulator for distributed robots in a simulated environments. I propose a short tutorial to write a first distributed code for VisibleSim.

3.15 On obliviousness

Nicola Santoro (Carleton University – Ottawa, CA)

Main reference P. Flocchini, G. Prencipe, N. Santoro, "Distributed Computing by Oblivious Mobile Robots", Synthesis Lectures on Distributed Computing Theory, Vol. 3, No. 2 , pp. 1-185, 2012.
URL http://dx.doi.org/10.2200/S00440ED1V01Y201208DCT010

The presence of some form of persistent memory (albeit small in size) is typically assumed in "micro-level" computations (e.g., programmable matter). In contrast, obliviousness (i.e., total absence of persistent memory) is a common restrictions in "macro-level" computations (e.g, autonomous mobile robots) in which I have been involved. On this regards, there are two interesting research questions I would like to share:

- Are meaningful oblivious computations possible at the micro-level?
- What are the precise limits of near-obliviousness (i.e., memory-size thresholds)?

3.16 Theory and practice of large scale molecular-robotic reconfiguration

Damien Woods (California Institute of Technology – Pasadena, US)

Joint work of Ho-Lin Chen, Moya Chen, David Doty, Scott Goodfriend, Nadine Dabby, Dhiraj Holden, Chris Thachuk, Erik Winfree, Damien Woods, Doris Xin, Chun-Tao Yang, Peng Yin

The talk discussed the theory and practice of molecular robotics. I am interested in large scale molecular reconfiguration, where dynamic self-assembling nanostructures change their shape in response to environmental stimuli. I'm very much interested in models that have the potential to be implemented in DNA: a shockingly-well understood and predictable material for nanoscale self-assembly. Specifically, the talk focused attention on questions on the Nubot model and on our initial progress on implementing this style of molecular robotics in the wet-lab.

3.17 Distributed coordination of mobile robots in 3D-space

Yukiko Yamauchi (Kyushu University – Fukuoka, JP)

Joint work of Taichi Uehara, Masafumi Yamashita
Main reference Y. Yamauchi, T. Uehara, M. Yamashita, "Brief Announcement: Pattern Formation Problem for Synchronous Mobile Robots in the Three Dimensional Euclidean Space", in Proc. of the 2016 ACM Symp. on Principles of Distributed Computing (PODC'16), pp. 447–449, ACM, 2016.
URL http://dx.doi.org/10.1145/2933057.2933063

We consider a swarm of autonomous mobile robots moving in the three-dimensional space (3D-space). Each robot is anonymous, oblivious (memory-less), and has neither any access to the global coordinate system nor any communication medium. Many researchers have considered formation problems (point formation, circle formation, pattern formation, etc.) in 2D-space, and it has been shown that the symmetry among the robots determines the patterns that the robots can form. We would like to present our recent results on formation problems in 3D-space, where we encounter rich symmetry represented by rotation groups.

Participants

- Luca Becchetti
Sapienza University of Rome, IT
- Julien Bourgeois
FEMTO-ST Institute – Montbéliard, FR
- Sarah Cannon
Georgia Institute of Technology – Atlanta, US
- Ioannis Chatzigiannakis
Sapienza University of Rome, IT
- Nikolaus Correll
Univ. of Colorado – Boulder, US
- David Doty
Univ. of California – Davis, US
- Yuval Emek
Technion – Haifa, IL
- Sándor Fekete
TU Braunschweig, DE
- Robert Gmyr
Universität Paderborn, DE
- Heiko Hamann
Universität Paderborn, DE
- Jacob Hendricks
University of Wisconsin – River Falls, US
- Stephan Holzer
MIT – Cambridge, US
- Irina Kostitsyna
Free University of Brussels, BE
- Dominik Krupke
TU Braunschweig, DE
- Fabian Daniel Kuhn
Universität Freiburg, DE
- Matteo Lasagni
TU Graz, AT
- Othon Michail
CTI – Rion, GR
- Venkateswarlu Muni
Ben Gurion University of the Negev – Beer Sheva, IL
- André Naz
FEMTO-ST Institute – Montbéliard, FR
- Pekka Orponen
Aalto University, FI
- Matthew J. Patitz
University of Arkansas – Fayetteville, US
- Theodore P. Pavlic
Arizona State University – Tempe, US
- Benoît Piranda
FEMTO-ST Institute – Montbéliard, FR
- Andréa W. Richa
Arizona State University – Tempe, US
- Kay Römer
TU Graz, AT
- Trent Rogers
University of Arkansas – Fayetteville, US
- Nicola Santoro
Carleton Univ. – Ottawa, CA
- Christian Scheideler
Universität Paderborn, DE
- Arne Schmidt
TU Braunschweig, DE
- Robert Schweller
The University of Texas – Pan American – Edinburg, US
- Thim Frederik Strothmann
Universität Paderborn, DE
- Sebastian von Mammen
Universität Augsburg, DE
- Jennifer L. Welch
Texas A&M University – College Station, US
- Andrew Winslow
Free University of Brussels, BE
- Damien Woods
California Institute of Technology – Pasadena, US
- Yukiko Yamauchi
Kyushu Univ. – Fukuoka, JP