Report from Dagstuhl Seminar 18331

Algorithmic Foundations of Programmable Matter

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 18331, "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 this seminar was to bring together researchers from computational geometry, distributed computing, DNA computing, and swarm robotics who have worked on programmable matter to inform one another about the newest developments in each area and to discuss future models, approaches, and directions for new research. Similar to the first Dagstuhl seminar on programmable matter (16271), we did focus on some basic problems, but also considered new problems that were now within reach to be studied. During this seminar, we were able to achieve a previously unmatched level of intensity of collaboration, in part due to using a new electronic and interactive web-based platform. This has also allowed for continued research among the attendees based on the work begun during the seminar.

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1 Executive Summary

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The term "programmable matter" refers to any substance that can change its physical properties (shape, density, moduli, conductivity, optical properties, etc.) in a programmable fashion. The role of *algorithmic foundations* of programmable matter continues to grow in

importance due to ongoing progress in a wide range of applications. Examples of cutting-edge application areas with a strong algorithmic flavor include *self-assembling systems*, in which chemical and biological substances such as DNA are designed to form predetermined shapes or carry out massively parallel computations; and *swarm robotics*, in which complex tasks are achieved through the local interactions of robots with highly limited individual capabilities, including micro- and nano-robots. Progress in these application areas has been achieved through close collaboration with algorithmic theoreticians, enabling the investigation of fundamental problems related to system geometry using methods from the field of *computational geometry*, and yielding techniques for decentralized computation from the field of *distributed computing*.

A previous Dagstuhl seminar (16271, Algorithmic Foundations of Programmable Matter) had laid the foundations for further progress by bringing together experts from different fields and focusing on expert surveys and breakout groups. We built on the success of that seminar by expanding its focus on particular challenges that arise from the application areas of programmable matter. For this purpose, we brought together a combination of established experts from DNA computing, swarm robotics, computational geometry, and distributed computing. On the senior level, particants included a number of leading authorities who are established in more than one of the mentioned topics; on the junior level, we had a good selection of highly talented scientists who are able to advance the field by specific contributions.

The seminar started with a plenary introduction of all participants, their research areas and their specific challenges and expectations for the seminar. This was followed by a number of plenary sessions, in which experts gave overviews of broad developments and specific open problems.

- Erik Demaine gave an overview of challenges for **geometric algorithms** in the settings of reconfigurable robots (both modular and folding robots that can become any possible shape), robot swarms (which may be so small and simple that they have no identity), and self-assembly (building computers and replicators out of DNA tiles).
- Dave Doty and Chris Thachuk gave a survey of the basics of experimental and theoretical **DNA tile self-assembly**, concluding with suggestions for theoretical problems related to programmable control of the nucleation of assemblies. A second part consisted of a survey of DNA strand displacement, including the problem of orienting molecules on a surface with the use of DNA origami and some clever shapes that can "align" themselves into target placements.
- Andréa Richa presented an overview of **self-organizing particle systems**, describing programmable matter as an abstract collection of simple computational elements (particles) with limited memory that each execute fully distributed, local, asynchronous algorithms to self-organize and solve system-wide problems such as movement, (re)configuration, and coordination.
- Aaron Becker discussed the connection between **robot swarms and programmable matter**, in particular in a setting with a global input to a whole particle swarm, as well as open questions arising from the use of mobile robots to fold 2D planar stock into 3D bricks and to connect the bricks together.

Spread throughout the week, further presentations were given by Spring Berman (applications and open challenges in swarm robotics and a control-theoretic framework for robotic swarms and programmable matter), Julien Bourgeois (realizing programmable matter with modular robots), Luca Cardelli (sequenceable DNA algorithms), Kenneth Cheung

(programmable modular periodic metamaterials), Sándor Fekete (coordinated motion planning), Roderich Groß (capabilities of individual units in distributed robotic systems and making programmable matter self-propel efficiently), Dan Halperin (hard vs. easy tasks in multi-robot motion planning), Heiko Hamann (self-assembly and collective construction based on minimal surprise), Lila Kari (DNA smart-tile self-assembly and computational CRISPR), MinJun Kim (engineering particles for robot swarms and modular microrobotics), Alcherio Martinoli (fluid-mediated stochastic self-assembly), Friedhelm Meyer auf der Heide (continuous strategies for swarm robotics), Nils Napp (autonomous construction in unstructured environments), Pekka Orponen (algorithmic design of RNA nanostructures) and Christian Scheideler (a survey on hybrid programmable matter).

A key feature of the seminar was exceptionally intensive, interdisciplinary collaboration throughout the week, based on the use of the new interactive electronic tool `coauthor`. This tool[1], specifically developed for use in a workshop-like environment, is an excellent platform that provides a versatile medium for collaborative research discussions, and maintains easily accessible structured records for future reference. We have found that `coauthor` greatly facilitated the work done during the seminar, enabling not just identification of, but also dynamic research work on a number of new topics. These include (A) specific problems in the context of hybrid models for programmable matter, in which there is a set of active micro-robots that can move a large set of simple material tiles that cannot move themselves; (B) aspects of distributed boundary detection for self-organizing swarms; (C) fundamental issues related to the computational equivalence of completely different self-assembly systems and robotic models; and (D) questions of self-aligning geometric shapes that would allow more robust methods for DNA origami and self-assembly. For some aspects, we were able to resolve long-standing open problems; for others, we made significant progress that will undoubtedly lead to future publications. As a consequence, the seminar has triggered a number of new collaborations and a variety of followup projects that will undoubtedly contribute to further collaborative research activities.

[1] https://github.com/edemaine/coauthor/

2 Contents

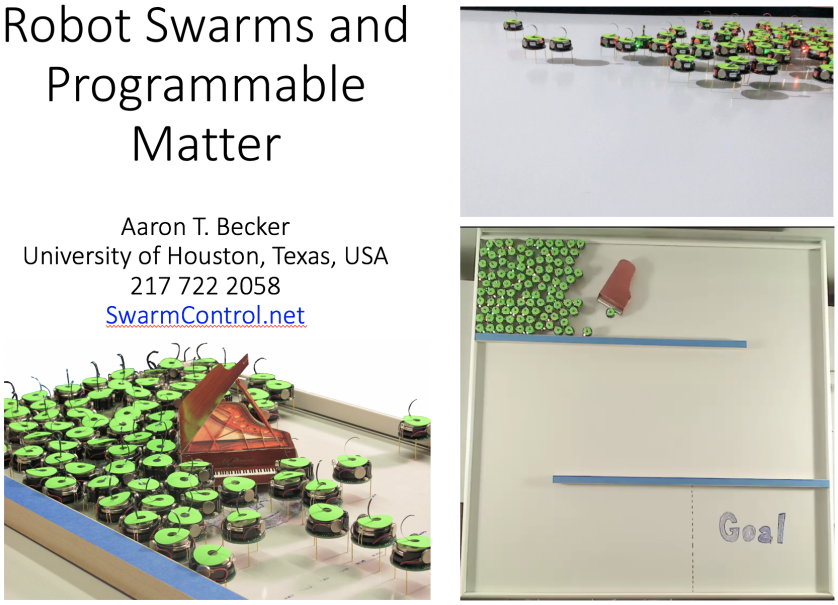
3 Overview of Talks

3.1 Robot Swarms and Programmable Matter

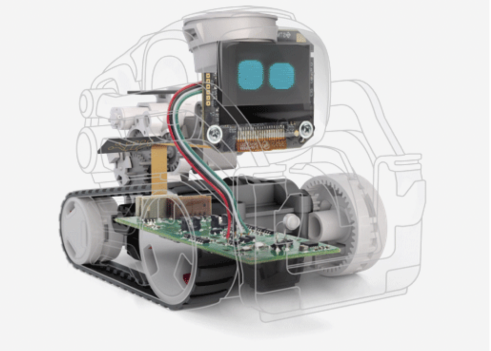
Aaron Becker (University of Houston, US)

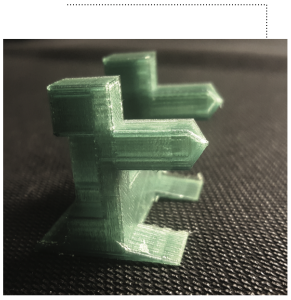
Joint work of Manzoor, Sheryl; Kim, Min Jun; Schmidt, Arne; Huang, Li; Krupke, Dominic; Fekete, Sándor; Ike, Rhema; Kantari, Saleh
Main reference Arne Schmidt, Sheryl Manzoor, Li Huang, Aaron T. Becker, Sándor P. Fekete: "Efficient Parallel Self-Assembly Under Uniform Control Inputs", CoRR, Vol. abs/1807.01584, 2018.
URL http://arxiv.org/abs/1807.01584

1. Global inputs, where each agent receives the same control input, are often used for tiny robots because it is difficult to fit power, actuation, and computation in tiny robots. This talk gives an overview of global inputs for steering planar robots to perform manipulation, generate formations, assemble into desired shapes, and build maps.



2. It is easier to equip larger robots with computation, sensing, and actuation. The second half of the talk explored open questions using mobile robots to fold 2D planar stock into 3D bricks and connect the bricks together. In this case the planar stock (paper) can be programmed by cutting it, scoring fold lines, and attaching fiducials and handles. Open questions include:
   a.) What classes of shapes can [not] be folded using forces applied to perimeter?
   b.) How can impossible shapes be approximated?
   c.) Minimum number of pushing actions?
   d.) Minimum number of robots?
   e.) How much harder is the distributed version of this problem than the centralized version?





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2 A. Schmidt, S. Manzoor, L. Huang, A. Becker, S. Fekete, "Efficient Parallel Self- Assembly Under Uniform Control Inputs", IEEE RA-L, 2018. https://arxiv.org/abs/1807.01584

3 P. Keldenich, S. Manzoor, L. Huang, D. Krupke, A. Schmidt, S. Fekete, A. Becker, "On Designing 2D Discrete Workspaces to Sort or Classify Polyominoes", 2018 IEEE IROS 2018

4 A. Mahadev, D. Krupke, S. Fekete, A. Becker, "Mapping and Coverage with a Particle Swarm Controlled by Uniform Inputs", IROS, 2017 10.1109/IROS.2017.8202280

5 Saleh Kantari, Rhema Ike, Aaron Becker, "Designing for Digital Assembly with a Construction Team of Mobile Robots", Association for Computer Aided Design in Architecture (ACADIA) October 18 – 20, 2018, Universidad Iberoamericana, Mexico City

3.2 Swarm Robotics: Applications, Open Challenges, and a Control-Theoretic Framework for Programmable Matter

Spring Berman (Arizona State University – Tempe, US)

Joint work of Spring Berman, Karthik Elamvazhuthi, Andrea L. Bertozzi, Hendrik Kuiper, Matthias Kawski, Fangbo Zhang, Matt Haberland, Ragesh K. Ramachandran, Vaibhav Deshmukh, Shiba Biswal, Zahi Kakish, Chase Adams, Sean Wilson, Theodore P. Pavlic, Ganesh P. Kumar, Aurélie Buffin

Robotic swarms are currently being developed to perform a variety of tasks over large spatial and temporal scales. However, significant technical challenges remain before these systems can be robustly deployed in unstructured, dynamic environments. We are addressing the problem of controlling swarms in scenarios where the robots lack global localization, prior data about the environment, and reliable inter-robot communication. As in natural swarms, the highly resource-constrained robots would be restricted to information obtained through

local sensing and signaling. We are developing a rigorous control and estimation framework, which may be useful for designing programmable matter, for swarms that are subject to these constraints. This framework will enable swarms to operate largely autonomously, with user input consisting only of high-level directives that map to a small set of robot parameters. We use stochastic and deterministic models from chemical kinetics and fluid dynamics to describe the robots' roles, task transitions, and spatiotemporal distributions at both the microscopic (individual) and macroscopic (population) levels. We have applied this framework to design stochastic strategies for coverage, assembly, task allocation, mapping, and scalar field estimation, as well as decentralized, ant-inspired approaches to cooperative manipulation.

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3.3 Realizing Programmable Matter with Modular Robots

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

Main reference Julien Bourgeois, Benoît Piranda, André Naz, Nicolas Boillot, Hakim Mabed, Dominique Dhoutaut, Thadeu Tucci, Hicham Lakhlef: "Programmable matter as a cyber-physical conjugation", in Proc. of the 2016 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2016, Budapest, Hungary, October 9-12, 2016, pp. 2942–2947, IEEE, 2016.
URL http://dx.doi.org/10.1109/SMC.2016.7844687

Technological advances, especially in the miniaturization of robotic devices foreshadow the emergence of large-scale ensembles of small-size resource-constrained robots that distributively cooperate to achieve complex tasks. These ensembles are formed by independent, intelligent and communicating units which act as a whole ensemble which can be used to build programmable matter, i.e., matter able to change its shape. In my talk, I present our research effort in building Programmable Matter (PM) based on modular robots. To do this, we use micro-technology to scale down the size of each element, and we study geometry, structure, actuation, power, electronics and integration. To manage the complexity of this kind of environment, we propose a complete environment including programmable hardware, a programming language, a compiler, a simulator, a debugger and distributed algorithms.

3.4 Sequenceable DNA Algorithms

Luca Cardelli (Microsoft Research UK – Cambridge, GB)

We give an introduction to DNA Strand Displacement: a technique that is used to program interactions between DNA strands in such a way, e.g., as to emulate the kinetics of an arbitrary finite network of chemical reactions. We discuss current capabilities and trends in DNA nanotechnology, including "high throughput" equipment that can read and write DNA massively in parallel.

High throughput DNA synthesis and sequencing render easily feasible a new class of algorithms that use $O(n^2)$ structures in input and output. We give two examples of such algorithms, for detecting the coincidence of events, and for detecting the preorder of events, over the course of an experiment in a biochemical soup.

3.5 Programmable Modular Periodic Metamaterials

Kenneth C. Cheung (NASA – Moffett Field, US)

Current practice in material and manufacturing efficiency is far from theorized physical limits, as demanded by long term and large scale space exploration applications. Significant progress may be achievable with reversible material assembly. Various programmable matter techniques utilize many of a small set of discrete modules that can be used to compute or program any area or volumetric shape, with any internal pattern. Metamaterials appear to be a promising demonstration target for discretized programmable material methods. In general these materials provide the capability of prescribing unique combinations of material properties to suit custom applications. Mechanical metamaterials are an example of periodic geometry governed materials that have seen near theoretically ideal properties when implemented through modular construction. These materials offer hierarchical decomposition in modeling, with bulk properties that can be predicted from component measurements, and programmed by relative placement of discrete part types with differing properties. Nano- and micro- scale mechanical metamaterials and periodic structures in general are clear targets for molecular assembly (with foundational work already in place). Macro-scale implementation may be a very interesting application for distributed robotics, as physical realizations of discrete theoretical models. These robots have characteristic dimension on the order of that of the modular cell or voxel, and use the regularity of the built assembly to simplify path planning, locomotion and manipulation (with low precision requirements), and allow low numbers of states and degrees of freedom (DOF) per robot. Many interesting open problems exist for determining optimality and complexity of planning and scheduling with various structural geometries and multi-robot system architectures.

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3.6 Replicators, Transformers, and Robot Swarms: Science Fiction through Geometric Algorithms

Erik D. Demaine (MIT – Cambridge, US)

Science fiction is a great inspiration for science. How can we build reconfigurable robots like Transformers or Terminator 2? How can we build Star Trek-style replicators that duplicate or mass-produce a given shape at the nano scale? How can we orchestrate the motion of a large swarm of robots? Recently we've been exploring possible answers to these questions through computational geometry, in the settings of reconfigurable robots (both modular and folding robots that can become any possible shape), robot swarms (which may be so small and simple that they have no identity), and self-assembly (building computers and replicators out of DNA tiles).

3.7 DNA tile self-assembly

David Doty (University of California – Davis, US)

I survey the basics of experimental and theoretical DNA tile self-assembly, starting with experimental efforts initiate by Ned Seeman to create unbounded period crystal lattices with DNA tiles, experimental efforts initiated by Erik Winfree to create algorithmic self-assembling tiles, and basic theoretical results about the computational ability of the tiles. I conclude with suggestions for theoretical problems on programmable control of nucleation that, if resolved, could be immediately tested in a wet lab, with luck greatly increasing the yield of tile-based self-assembled structures, compared to the current low yield state-of-the-art.

3.8 Coordinated motion planning: Reconfiguring a swarm of labeled robots with bounded stretch

Sándor P. Fekete (TU Braunschweig, DE)

Joint work of Aaron T. Becker, Erik D. Demaine, Sándor P. Fekete, Phillip Keldenich, Matthias Konitzny, Lillian Lin, Henk Meijer, Christian Scheffer

We motivate, visualize and demonstrate recent work for minimizing the total execution time of a coordinated, *parallel* motion plan for a swarm of N robots in the absence of obstacles. Under relatively mild assumptions on the separability of robots, the algorithm achieves *constant stretch*: If all robots want to move at most d units from their respective starting positions, then the total duration of the overall schedule (and hence the distance traveled by each robot) is $O(d)$ steps; this implies constant-factor approximation for the optimization problem. Also mentioned is an NP-hardness result for finding an optimal schedule, even in the case in which robot positions are restricted to a regular grid. On the other hand, we show that for densely packed disks that cannot be well separated, a stretch factor $\Omega(N^{1/4})$ is required in the worst case; we establish an achievable stretch factor of $O(N^{1/2})$ even in this case. We also sketch geometric difficulties of computing optimal trajectories, even for just two unit disks.

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3.9 Less is more? Defining your building blocks

Roderich Groß (University of Sheffield, GB)

Joint work of Roderich Groß, Melvin Gauci, Jianing Chen, Matthew Doyle, Anil Özdemir

When designing a distributed robotic system to exhibit collective behavior, choices need to be made regarding the capabilities of the underlying individual units. These choices impact on the potential to scale the units down in size and up in numbers. This talk first shows how to design behavioral rules of extreme simplicity. We look at (i) rules emulating granular material, and (ii) rules that require no arithmetic computation. Second, we address the open challenge to make programmable matter self-propel efficiently, by introducing a novel propulsion concept. This leads to robots of arbitrary morphology, which provably move towards a goal in their environment even though they lack arithmetic computation.

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3.10 Hard vs. Easy in Multi-Robot Motion Planning

Dan Halperin (Tel Aviv University, IL)

Early results in robot motion planning had forecast a bleak future for the field by showing that problems with many degrees of freedom, and in particular those involving fleets of robots, are intractable. Then came sampling-based planners, which have been successfully, and often easily, solving a large variety of problems with many degrees of freedom. We strive to formally determine what makes a motion-planning problem with many degrees of freedom easy or hard. In the first part of the talk I'll describe our quest to resolve this (still wide open) problem, and some progress we have made in the context of multi-robot motion planning. In the second part of the talk I'll review recent algorithms that we have developed for multi-robot motion planning, which come with near- or asymptotic-optimality guarantees.

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3.11 Self-assembly and collective construction based on minimal surprise

Heiko Hamann (Universität Lübeck, DE)

Joint work of Heiko Hamann, Tanja Kaiser, Richard Borkowski
Main reference Heiko Hamann: "Evolution of Collective Behaviors by Minimizing Surprise", Alife, MIT Press, pp. 344–351, 2014.
URL https://doi.org/10.7551/978-0-262-32621-6-ch055

What about we don't tell our robots what they have to do? With the approach of minimizing surprise, we only ask the robots to create situations that allow for easy predictions. Each robot has a controller (artificial neural network, ANN) to select the next action and a prediction machine (ANN) to predict future sensor input (of the next time step). Here, these pairs of networks are tuned by an evolutionary algorithm. The fitness (reward) is based

on correct predictions only. There is no desired or predefined behavior. Applied to robot swarms, we observe typical swarm behaviors, such as aggregation, dispersion, and flocking. In a self-assembly setup we observe also aggregation, dispersion, line formations, and the formation of triangular lattices.

3.12 (DNA) Smart-tile Self-Assembly and Computational CRISPR

Lila Kari (University of Waterloo, CA)

Joint work of Lila Kari, Amirhossein Simjour
Main reference Lila Kari, Amirhossein Simjour: "Smart Tile Self-Assembly and Replication", Fundam. Inform., Vol. 154(1-4), pp. 239–260, 2017.
URL http://dx.doi.org/10.3233/FI-2017-1564

We present the concept of (in-vitro DNA) self-assembly of smart tiles, i.e., tiles which possess a local computational device, in addition to having edge glues that can be activated or deactivated by signals (joint work with Amir Simjour). The local tile computational device can range from nonexistent, to being a counter, a simple look-up table, a finite state machine, all the way to being a Turing machine. Thus, this model may offer a general framework to discuss and compare various tile self-assembly systems. We demonstrate the potential of self-assembly with smart tiles to efficiently perform robotic tasks such as the replication of convex shapes. The smart tile assembly system that we propose for convex shape replication does not make any assumption on the glues and signals of the interior tiles of the input supertile, adds tiles one at a time, and uses a scaffold to assemble a replica adjacent to the input supertile.

In the second part of the talk, we draw a parallel between the mechanism of targeted gene editing by CRISPR-CAS9 and Contextual Insertion/Deletion Systems, a DNA-inspired computational model with Turing machine computational power. We suggest that a version of contextual ins/del systems could be defined that accurately utilizes the CRISP/CAS9 mechanism, making the latter a suitable candidate for easy, efficient, and customizable in-vivo DNA computation.

3.13 Engineering Particles for Robot Swarms and Modular Microrobotics

MinJun Kim (SMU – Dallas, US)

The realization of reconfigurable modular microrobots could aid drug delivery and microsurgery by allowing a single system to navigate diverse environments and perform multiple tasks. So far, microrobotic systems are limited by insufficient versatility; for instance, helical shapes commonly used for magnetic swimmers cannot effectively assemble and disassemble into different size and shapes. Here by using microswimmers with simple geometries constructed of spherical particles, we show how magnetohydrodynamics can be used to assemble and disassemble modular microrobots with different physical characteristics. We develop a mechanistic physical model that we use to improve assembly strategies. Furthermore, we

experimentally demonstrate the feasibility of dynamically changing the physical properties of microswimmers through assembly and disassembly in a controlled fluidic environment. Finally, we show that different configurations have different swimming properties by examining swimming speed dependence on configuration size.

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3.14 Fluid-Mediated Stochastic Self-Assembly: Towards Bridging Centimetric and Submillimetric Scales

Alcherio Martinoli (EPFL – Lausanne, CH)

Joint work of Bahar Haghighat, Massimo Mastrangeli, Grégory Mermoud, Felix Schill, Alcherio Martinoli
Main reference Bahar Haghighat, Massimo Mastrangeli, Grégory Mermoud, Felix Schill, Alcherio Martinoli: "Fluid-Mediated Stochastic Self-Assembly at Centimetric and Sub-Millimetric Scales: Design, Modeling, and Control", Micromachines, Vol. 7(8), p. 138, 2016.
URL http://dx.doi.org/10.3390/mi7080138

Miniature robots at centimeter scale can be effective demonstrators: they can be designed and manufactured leveraging off-the-shelf components and standard mechatronic recipes. Unfortunately, the application areas for this scale are limited while many potential applications are available at the submillimeter scale. Devices at the submillimeter scale cannot be endowed with similar resources as their centimetric counterpart as the manufacturing technology at this scale is still very expensive, needs hardware customization, and multiple functionalities are difficult to integrate in a single device with canonical top-down manufacturing techniques. One of the promising techniques to manufacture more complex microrobots is to leverage existing Micro-Electro-Mechanical Systems (MEMS) achieving different functionalities, produced with standard micromachining procedures, and use them as building blocks for a fluid-mediated

self-assembling process. In order to efficiently guide the self-assembly process, stochastic modeling and control techniques developed for centimeter devices can help. In particular, in this talk I illustrate a vision-based closed-loop framework able to both automatically create models at multiple abstraction levels and optimize the agitation of the liquid in which the self-assembly process takes place for both passive centimeter and sub-millimeter building blocks. I then describe also recent self-assembly results achieved with a demonstrator having the same dimensions of the previous one at centimeter scale but consisting of robotic modules endowed with a programmable ruleset and able to control their on-board latching properties. While these latter properties are difficult to transpose to submillimeter modules, this successive research effort has allowed us to develop an effective software framework for self-assembly experiments and gain further insight in distributed control strategies potentially deployable at submillimeter level in the future.

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3.15 Continuous Strategies for Swarm Robotics

Friedhelm Meyer auf der Heide (Universität Paderborn, DE)

Joint work of Friedhelm Meyer auf der Heide, Peter Kling, Barbara Kempkes, Pavel Podlipyan and many others.
Main reference Bastian Degener, Barbara Kempkes, Peter Kling, Friedhelm Meyer auf der Heide: "Linear and Competitive Strategies for Continuous Robot Formation Problems", TOPC, Vol. 2(1), pp. 2:1–2:18, 2015.
URL http://dx.doi.org/10.1145/2742341

I consider large swarms of relatively simple mobile robots deployed to the plane. Each robot has only very limited local information about the swarm. More precisely, a swarm consists of identical, anonymous robots: they are points in the plane and their local information consists only of the relative positions of the robots within a small, bounded viewing radius. My focus is on strategies of such swarms that result in formations problems like "gathering in one point". I present several strategies for such formation problems, and discuss upper and lower bounds for their runtime.

First, I introduce continuous strategies, where each robot continuously observes its neighborhood and continuously adapts its speed (with given speed limit) and direction following a local rule. I present the class of contracting strategies, show that they perform

gathering in quadratic time, and present best and worst case examples. With the go-on-bisector-strategy, I present a time optimal gathering strategy. Finally, I introduce the variant of the go-to-the center strategy that only considers edges of the Gabriel subgraph of the unit-disk graph, and give experimental evidence that it almost never produces early collisions. Most of the presented work is based on the following two publications:

References

1 Shouwei Li, Christine Markarian, Friedhelm Meyer auf der Heide, Pavel Podlipyan: A Continuous Strategy for Collisionless Gathering. ALGOSENSORS 2017: 182-197
2 Bastian Degener, Barbara Kempkes, Peter Kling, Friedhelm Meyer auf der Heide: Linear and Competitive Strategies for Continuous Robot Formation Problems. TOPC 2(1): 2:1-2:18 (2015)

3.16 Autonomous Construction in Unstructured Environments

Nils Napp (Buffalo State – The State University of New York, US)

The talk presents research on reliably building support structures in cluttered and un-prepared environments using autonomous robots, both from a theoretical and practical perspective. The focus of the talk is modeling the physical world and the robot's interactions with it, in such a way that allows the system to synthesize correct actions on the fly based on local sensor information. Ideally, autonomous construction systems should be able to use a wide variety of building materials, yet the ability to plan and act is closely tied to particular building materials. The talk presents some of the challenges of modeling different material types and how they affect a robot's ability to formulate long-term plans.

3.17 Algorithmic design of RNA nanostructures

Pekka Orponen (Aalto University, FI)

Joint work of Pekka Orponen, Antti Elonen, Ibuki Kawamata, Lukas Oesinghaus, Abdulmelik Mohammed, Jani Seitsonen, Yuki Suzuki, Friedrich C. Simmel

Inspired by the remarkable success of DNA nanotechnology, using RNA as nanoscale construction material is attracting increasing attention. The promise of RNA is that it can be produced in quantity by natural processes at room temperature, e.g. by polymerase transcription in cell culture. The challenge, on the other hand, is that the folding process of single-stranded RNA is at the moment much less well understood than that of double-stranded DNA, and there are not similarly well-established robust design protocols as the origami technique in DNA nanotechnology.

Following a brief introduction to some basic concepts in RNA nanotechnology, we present an approach to single-stranded RNA self-assembly of general polyhedral shapes. The technique is based on first routing the RNA strand twice around a spanning tree of the polyhedron's mesh skeleton, in order to create stem helices representing the spanning-tree edges, and then complementing the design by building the non-spanning tree edges from kissing loop motifs. A design tool to support this protocol has been implemented and some initial designs synthesised and imaged.

3.18 Self-organizing Particle Systems

Andréa Richa (Arizona State University – Tempe, US)

Joint work of Andréa Richa, Sarah Cannon, Joshua Daymude, Zahra Derakhshandeh, Robert Gmyr, Cem Gokmen, Kristian Hinnenthal, Irina Kostitsyna, Shengkai Li, Alexandra Porter, Dana Randall, Will Savoye, Christian Scheideler, Thim Strothmann
URL https://sops.engineering.asu.edu/

Many programmable matter systems have been developed, including modular and swarm robotics, synthetic biology, DNA tiling, and smart materials. We describe programmable matter as an abstract collection of simple computational elements (particles) with limited memory that each execute fully distributed, local, asynchronous algorithms to self-organize and solve system-wide problems such as movement, configuration, and coordination. Self-organizing particle systems (SOPS) have many interesting applications like coating objects for monitoring and repair purposes, and forming nano-scale devices for surgery and molecular-scale electronic structures. In this talk, we describe our work on establishing an algorithmic foundation for programmable matter. We investigate how macro-scale system behaviors can naturally emerge from local micro-behaviors by individual particles. We start by investigating shape formation, leader election and coating in SOPS. We then utilize tools from statistical physics and Markov chain analysis to translate Markov chains defined at a system level into asynchronous, distributed, local algorithms for self-organizing particle systems that drive the emergent phenomenon of compression, expansion, bridging, separation, and phototaxing, also establishing direct ties to the notion of "active matter" in physics. Ongoing work also addresses the convex hull problem in the context of self-organizing particle systems.

3.19 Survey on Hybrid Programmable Matter

Christian Scheideler (Universität Paderborn, DE)

Joint work of Robert Gmyr, Kristian Hinnenthal, Irina Kostitsyna, Fabian Kuhn, Dorian Rudolph, Thim Strothmann, Christian Scheideler

In my survey I present a new model for programmable matter that consists of simple nano-robots acting on stateless tiles. Computationally, the nano-robots are only as powerful as finite automata. A nano-robot acts in look-compute-move cycles: it first looks at its immediate neighborhood to determine which positions around it are occupied by tiles, and based on that and its current state it decides on which state to switch to and which move to perform. As a move, a nano-robot may either just move to a neighboring position, pick up a tile below it, or place a tile it is carrying at the position below it. I show that even with just a single nano-robot various shape formation and shape detection problems can be solved. The results presented in this talk appear at the MFCS 2018 and DNA 2018 conferences [1, 2].

References

1 Robert Gmyr, Kristian Hinnenthal, Irina Kostitsyna, Fabian Kuhn, Dorian Rudolph, and Christian Scheideler. Shape Recognition by a Finite Automaton Robot. In Proceedings Mathematical Foundations of Computer Science (MFCS 2018), pp. 52:1–52:15.

2 Robert Gmyr, Kristian Hinnenthal, Irina Kostitsyna, Fabian Kuhn, Dorian Rudolph, Christian Scheideler, and Thim Strothmann. Forming Tile Shapes with Simple Robots. In Proceedings DNA Computing and Molecular Programming (DNA 2018), pp. 122–138.

3.20 Using DNA to compute and to organize molecules on a surface

Chris Thachuk (University of California – Davis, US)

Joint work of David Kirkpatrick, Ashwin Gopinath, Paul W. K. Rothemund, Erik Winfree

The promise of molecular programming lies in its ability to not only process information autonomously, but to do so in a biochemical context in order to sense and actuate matter. The most sophisticated molecular computing systems that have been experimentally realized have been built upon the DNA strand displacement (DSD) primitive, where a soup of rationally designed nucleotide sequences interact, react, and recombine over time in order to carry out complex computation. After giving a survey of DSD we present the problem of absolutely orienting molecules on a surface with the use of DNA origami and some clever shapes that can 'align' themselves into a target placement.

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