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Self-Assembly at the Macroscopic Scale

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Abstract

In this paper, we review half a century of research on the design of systems displaying (physical) self-assembly of macroscopic components. We report on the experience gained in the design of 22 such systems, exhibiting components ranging from passive mechanical parts to mobile robots. We present a taxonomy of the systems, and discuss design principles and functions. Finally, we indicate potential directions for future research.

1 Introduction

Self-assembly processes are responsible for the generation of order in nature. They involve components at different scales, such as molecules, cells, organisms, and weather systems. Scientists across many disciplines believe that the study of physical models of self-assembly can help in understanding nature and advancing technology.

Following Whitesides and Grzybowski [82], self-assembly can be defined as a process by which pre-existing discrete components organize into patterns or structures without human intervention. We focus on processes (i) in which components (physically) bind together, and (ii) that can be controlled by proper design of the components.

Self-assembly processes are governed by information coded in the components. In biological systems, for instance, the component design undergoes evolution as the structure resulting from the components' interactions is selected for specific functions [1,12,70]. In general, the component design satisfies at least one of the following properties:

- *selective binding*: components selectively bind to each other and/or selectively disband from each other (e.g., based on shape recognition);
- *adjustability*: once bound into an aggregate, components adjust their positions relative to one another.

To illustrate the importance of these properties, we look at some examples from nature. Selective binding is widely observed, for instance, in the assembly of the DNA double helix. It regulates the replication of genetic information and makes the process intrinsically self-correcting [66]. Another example are ants of the species *Œcophylla longinoda* [51,52] that, if offered two alternative sites to bridge an empty space, typically end up in a single, large aggregate in either one of the two sites. This collective choice is triggered by preferences to enter (or leave) aggregates of different size. Adjustability is responsible for the well-ordered structure of crystals [81], and for the regeneration of functional sponges of the species *Sycon raphanus* after a manipulative isolation of their cells [83].

Previous surveys of self-assembling systems provide a general overview of systems ranging from the molecular to the planetary scale [82], treat natural systems [1, 70], or focus on systems at the molecular or mesoscopic scale [6, 66]. In this paper, we review artificial systems at the macroscopic scale. These systems consist of centimeter-sized components, which currently are the biggest available in man-made self-assembly systems.

Systems at the macroscopic scale present some interesting characteristics: (i) the component design can be precisely controlled, (ii) the logic of existing components can be re-programmed by simple means, (iii) modules can exhibit complex dynamic behaviors involving thousands of internal states, (iv) modules can be equipped with a range of sensors providing feedback from the environment, (v) modules can interact via communication, and (vi) self-assembly processes can be easily monitored and analyzed (by the components themselves or by external observers).

In this survey, we present a comprehensive collection of systems for which self-assembly has been demonstrated. The diversity of the examples and the present lack of a theoretical framework are parts of the picture that we wish to convey. In general, two distinct classes of systems exist (Sections 2 and 3, respectively): (i) systems in which the components (that assemble) are externally propelled, and (ii) systems in which the components (that assemble) are self-propelled. Self-propulsion is of particular relevance for systems at the macroscopic scale. We provide a taxonomy that allows to identify relations among the different systems, and to extract some principles in the design of self-assembling systems (Section 4). We identify potential direction for future research (Section 5), and conclude the paper (Section 6).

2 Self-Assembly of Externally Propelled Components

In this section, we focus on systems in which the components are externally propelled. Components up to the microscopic scale, if suspended in a fluid, exhibit “Brownian motion” as the system is agitated thermally [10, 19]. At the macroscopic scale, however, the underlying thermal effects are irrelevant. Thus, propulsion requires external agitation apparatuses. To increase the rate at which components encounter each other, the system environment is bounded, and components are relatively numerous.

In this section, we present ten systems whose components are externally propelled. The components that self-assemble are the system’s building blocks as well as the intermediate products of the self-assembly process. In the following, we use the term *modules* to refer to a system’s basic building blocks.

2.1 Penrose’s Template-Replicating Modules

Half a century ago, L. S. Penrose and R. Penrose built the first known physical model of a self-replicating machine [65]. The system is of purely mechanical nature. It comprises two types of modules, A and B. Modules of both types are put in random sequence on a linear track that is blocked at both ends. Each module has a state, which is expressed by its orientation relative to the track. A module’s orientation can be horizontal, or inclined to either the left or the right side. The system is subject to side-to-side agitation. In their default orientation (i.e., horizontal), modules do not link under the influence of shaking alone. If a seed object composed of an A and B module is added, identical objects will self-assemble at any point on the track where an A module happens to be immediately on the left of a B module. If the experiment is repeated, with the seed object being inclined in the opposite direction, a complementary aggregate is built. The replicant equals the template with regard to the number and type of modules, as well as the modules’ state. In a follow-up work, L. S. Penrose [64] designed a system composed of homogeneous modules. The well thought-out design allowed a seed of two modules to replicate regardless of the distribution of additional modules on either side of the track. Moreover, the system was partially extended to two dimensions.

2.2 Hosokawa *et al.*’s Self-Assembling Hexagons

Hosokawa *et al.* [45] analyzed the dynamics of self-assembly formation with a system composed of simple, homogeneous modules. The modules reside in a flat box, which rotates in a vertical plane. Differently from Penrose’s system, the modules do not have any state. However, a simple logic is implemented by the anisotropic binding preferences. The module’s layout is an equilateral triangle with permanent magnets of opposite polarization in two of its sides. Consequently, at most six modules can bind together, forming this way a hexagon.

The authors describe potential transitions among initial, intermediate, and final products by a system of "chemical" reactions. The state of the system is expressed in the quantities of every product. The system dynamics is described using estimates for the reaction probabilities. The *yield* of hexagons, that is, the amount of hexagons the system produces, is calculated and compared to the average yield obtained by repeated experiments. The authors report that the equations can be solved numerically within reasonable time for 20 modules.

The authors propose a second design, in which a module can be in either an active or passive state. Stable bindings between two modules can only occur if at least one is in the active state. Modules in the passive state get activated once they bind with an active module. Initially, only seed modules (one per desired hexagon) are in the active state. The yield of hexagons is greater than in the previous system. However, it is not optimal, as multiple seed modules are not prevented from becoming part of a same aggregate.

2.3 Breivik's Template-Replicating Polymers

Breivik [9] developed a system of template-replicating polymers. The system comprises two types of modules, A and B. Modules can bind in two ways. Binding ":" forms discrete pairs between single A and single B modules ($A : B$), whereas binding "$-$" forms continuous polymers of arbitrary sequence ($-A - B - B - A - B-$). Binding ":" is more probable and less stable than binding "$-$". The bindings are implemented using permanent magnets of different Curie points (i.e., the temperature above which the characteristic ferromagnetic ability disappears). The module's logic is coded in hardware (i.e., in the particular shape and binding mechanism).

In an experiment, 70 modules (35 of each type) floated freely in an agitated liquid 2-D environment. The ambient temperature was subject to change to temporarily exceed the Curie points of the magnets. Through repetitive thermo-cycles, "polymers formed and acted as templates for the formation of new sequences".

2.4 White *et al.*'s Self-Assembling Programmable Modules

White *et al.* studied two systems in which the module's binding preferences are coded in a program executed by an on-board microcontroller, and thus can easily change in time [80]. The modules float passively on an air table that is fixed to an orbital shaker. In the first system, each module is of cuboid shape and can connect to other modules on four of its faces. The binding mechanisms are switchable electromagnets. In the second system, modules are of triangular shape and equipped with swiveling permanent magnets. The basic modules are un-powered. Once they bind with a seed module that is connected to a power supply, they become active.

The systems displayed *self-reconfiguring* entities, that is, modular entities that change structure, in this case, by having modules disband and reunite at different places. Both systems demonstrated self-assembly and subsequent self-reconfiguration with three modules. Using the first system, further experiments were carried out to determine the mean time until the first binding occurs in an environment with either two or three modules.

The authors consider an analytical model, which suggests that the number of modules in an entity increases quadratically in time, if the growth is unconstrained. A simple computational model of the physical system is presented. It confirms the quadratic order for the unconstrained growth for two different module densities (provided that a sufficient number of modules is available). If modules are programmed to self-assemble into structures of specific shapes, the growth rate largely depends on the particular algorithm used.

2.5 Griffith *et al.*'s Electromechanical Assemblers

Griffith *et al.* studied template-replication with a system of programmable modules that store state [33, 34]. The modules slide passively on an air table. Each module has two active and two passive binding sides. Each active side is equipped with a physical latch that is activated by an electromagnet once a mating module is sufficiently close.

The system demonstrated the self-replication of a 5-module entity (each module coding 1 bit of information). Each module executed a finite-state machine. In another experiment, modules self-assembled into a 2-D lattice comprising up to 26 modules [34].

2.6 White *et al.*'s Systems for Self-Assembly in 3-D

White *et al.* developed two modular systems and an apparatus containing an agitated fluid in which modules are subject to random motion in 3-D [79]. In both systems, modules are of cubic shape and with programmable logic. In the first system modules bind using switchable electromagnets. Self-assembly of two modules was systematically assessed in fifty trials. One module was manually attached to a magnetic plate and thereby connected to an external power supply. The other module could freely move within the apparatus. In 24% of the trials, the modules self-assembled and subsequently self-reconfigured by disconnecting from each other and re-assembling into a configuration that was different from the initial one. Communication among connected modules was used to synchronize the actions required for disconnecting. In addition, passive aggregation (i.e., a process by which components stick irreversibly upon random encounter) was demonstrated with up to four, free moving un-powered modules.

In the second system the fluid of the apparatus flows through pipelines that are integrated in the modules. Six pipelines—one for each face—join in the module's center. Each pipeline is equipped with a valve that can be opened or closed to control the flow. The authors demonstrated the ability of two modules to form and change configuration by self-assembling. One module was fixed to the apparatus and a pump was connected to the opening of one face. The force of the fluid was directed towards the module and let another module approach and bind with the previous one. There was no binding force other than the pressure caused by the flow.

2.7 Bishop *et al.*'s Self-Assembling Hexagons

Bishop *et al.* [5] addressed the problem of controlling a system of programmable modules to form non-trivial target structures. The modules slide passively on an air table. They are triangular, having a side length of 12 cm. Each side is equipped with a binding mechanism comprising one fixed and two movable permanent magnets. Power is provided on-board. Once a connection is established, modules exchange information on their state and decide whether to remain bound or to detach. The logic is coded in a graph grammar, which is stored on and interpreted by each module.

Equipped with an adequate grammar, N modules can assemble up to $\lfloor N/6 \rfloor$ hexagons autonomously. Experiments were performed with $N = 6$ modules. The design problem, that is, the problem of finding a grammar that causes the modules to assemble into a desired product, is further discussed in [50].

2.8 Bhalla & Bentley's Self-Assembling Special Purpose Modules

Bhalla and Bentley [4] studied self-assembly for the formation of objects of pre-defined shape. A module can have an arbitrary concave and/or convex polygon shape, and a single magnetic disk (of arbitrary polarity) attached to an arbitrary position. The modules are manually designed to assemble an entity of pre-defined shape. Typically, some modules are interchangeable, that is, their design is identical. During experimentation, the modules reside on a tray which is subject to agitation. Five systems producing five distinct target shapes have been constructed. The authors discuss an automated design approach based on artificial evolution.

3 Self-Assembly of Self-Propelled Components

In this section, we focus on systems with self-propelled components. In these systems, external agitation apparatuses are not required. In nature and technology, this type of system typically occurs at the macroscopic scale.

In general, two types of modular systems exist in which self-propelled components assemble:

1. Systems in which each module is self-propelled, and thus can be a component that approaches and assembles with other components. In these systems, modules can be considered mobile robots.

2. Systems in which individual modules have no or highly limited motion abilities. Nevertheless, entities comprising multiple assembled modules can be self-propelled, for instance, if the modules change their position or orientation with respect to each other. In these systems, modular entities can be considered modular reconfigurable robots [69, 90, 93].

In some systems, modules both with and without self-propulsion coexist.

3.1 Reproductive Sequence Device (RSD)

Almost half a century ago, Jacobson [46] designed models for self-replication. The Reproductive Sequence Device One (RSD I) is composed of two types of modules, called heads and tails. The modules move autonomously on a circular track with several sidings. Initially, the modules are arranged in random sequence. With the help of an operator, a seed object composed of a head and tail module assembles in a siding of the track. A reliable connection is established as the tail car keeps on pushing towards the halted head car. The seed object triggers another head and tail module to assemble into an identical object on the adjacent siding. This process continues until the system resources (i.e., modules or sidings) get exhausted. The system proved capable of correctly replicating the seed object in three adjacent sidings [46]. The system operated without human intervention. A considerable amount of functionality resided in the environment.

3.2 CEBOT

Fukuda *et al.* proposed the concept of modular reconfigurable robotics and realized the first implementation with CEBOT [22, 28]. CEBOT is a heterogeneous system comprised of modules with different functions (e.g., to move, bend, rotate, and slide). A series of prototypes has been implemented. The first prototype, the CEBOT Mark I [23, 24], is of cuboid shape with active and passive connectors on opposite sides. A shape memory alloy (SMA) actuator can cause a latch to catch a lateral groove in a pin from the mating module. It was shown that a module (equipped with two motorized wheels) could approach the back of another module [23, 24]. However, such a "rough approach" was found ineffective for coupling the two modules, as the binding mechanism required a very precise alignment. In CEBOT Mark II [21, 25, 26] and CEBOT Mark IV [27, 30], a mechanical hook is used instead for connecting. Additionally, a cone-shaped part fixed on the front of each module matches a counterpart on the back of each module to facilitate alignment during approach. In CEBOT Mark III [29], modules have a hexagonal shape. The six faces are provided with three active and three passive connectors. The binding mechanism is similar to the one employed in CEBOT Mark I. The pins of the active connectors are made of elastic material. The module is equipped with six nozzles providing propulsion on flat terrain.

Fukuda *et al.* demonstrated the successful docking of a mobile module with a stationary module, using the CEBOT Mark II [26], Mark III [29], and the Mark IV [30] platforms. In each case, coordination was achieved by making use of a set of infrared detectors and emitters. Communication among the (connected) modules of a modular robot was studied to enable it to approach and connect with an additional module [21].

3.3 PolyBot

PolyBot [87–90, 94] is a chain-based reconfigurable robot that can configure its shape with no external mechanical assistance. Each module has one degree of freedom involving rotation of two opposite binding plates through a +/-90 degree range. A shape memory alloy actuator integrated in each binding plate can rotate a latch to catch lateral grooves in the pins from the mating binding plate. Additional passive cuboid segments with six binding plates can be used to introduce branches to the structure and to connect with an (external) power supply. Active modules are equipped with IR detectors and emitters integrated in the binding plates.

Yim *et al.* [91] demonstrated the ability of a modular robot arm composed of six PolyBot G2 modules to approach and grasp another module on flat terrain. One end of this arm was attached to a wall of the arena. To let the other end reach a predetermined position and orientation, the joint angles for each segment were calculated by an inverse kinematics routine. Further alignment and approach was supported by making use of the IR detectors and emitters, and by the mechanical properties of the binding mechanism (pins sliding into chamfered holes). A similar experiment was accomplished using PolyBot G3 [89, 91, 94]. A modular arm composed of seven modules approached and docked with another module [86]. The modular arm could operate in 3-D. In the experiment, the arm and the target module were set up approximately in a same vertical plane.

3.4 CONRO

CONRO is a homogeneous, chain-based reconfigurable robot [13, 14, 63]. Each module comprises a processor, power supply, sensors, and actuators. The basic implementation consists of three segments connected in a chain: a passive connector, a body, and an active connector. The connectors can be rotated with respect to the body in the pitch and yaw axes by means of two motorized joints. A shape memory alloy actuator integrated in the active connector can rotate a latch to catch lateral grooves in the pins from the plate of the mating passive connector. IR emitters and detectors are integrated in the binding plates to support the docking and to enable communication between connected modules.

Rubenstein *et al.* [68] demonstrated the ability of two CONRO robots to self-assemble. Each robot consisted of a chain of two linearly-linked CONRO modules. To ensure that both chains perceive each other, they were set up at distances of not more than 15 cm, facing each other with an angular displacement not larger than 45°. The control was heterogeneous, both at the level of individual modules within each robot and at the level of the modular makeup of both robots. During the experimentation the two modular robots were tethered to an external power supply.

3.5 Super Mechano Colony (SMC)

Super mechano colony (SMC) [15,42,43] is a modular robotic concept composed of a *parent* module and several *child* modules attached to it. Child modules are an integral part of the system's locomotion. In addition, the child modules can disband to accomplish separate, autonomous missions, and reconnect once the missions are accomplished. Hirose *et al.* [15, 43] introduced an early prototype of the SMC concept. Two motorized and two passive wheels provide mobility on flat terrain. Each module is equipped with a manipulation arm that can be elevated, and a gripper attached to it. The upper body (including the gripper) can be rotated with respect to the chassis by means of a motorized vertical axis. For a similar prototype, a modular robot composed of a parent module and three child modules proved capable of *task-oriented reconfiguration* [84, 85]. The parent module was supposed to move in a straight line. The tracking performance depended on both the speed and the binding structure. Initially, the three child modules were manually arranged into a chain pulling the parent module. The two child modules at the back of the chain disconnected, followed a predefined path, and reconnected to the parent module directly. The system allowed for an optimal tracking performance at different speeds.

Recently, Groß *et al.* [40] ported a control algorithm for autonomous self-assembly from the swarm-bot platform to the SMC platform. Although there were substantial differences between the two systems, it was shown that it is possible to qualitatively reproduce the basic functionality of the source platform on the target platform. The controller was capable of letting a child module approach and assemble with another module, for approaching angles up to 150°. In 91 out of 92 trials the modules correctly established a connection. In a second experiment with one static and three moving child modules, in which the static module was manually equipped with specifically designed visual marks to seed the process, it was shown that, depending on the visual mark present, different formations emerged.

3.6 Bererton & Khosla's System for Cooperative Repair

Bererton and Khosla studied cooperative repair in a team of two autonomous, wheeled modules [2, 3]. Although, the modules cannot establish a firm connection with each other, the difficulties encountered in this study are similar to those that we face in self-assembly experimentation. One module (the *repair module*) is equipped with a fork-lift mechanism that can be partially inserted into a receptacle of a defective component of its (stationary) teammate. A black and white camera is mounted on top of the approaching module. It is connected to an external PC that processes the images and sends control commands to the approaching module via an RF link.

A simple state machine proved capable of controlling the repair module to replace a part of its teammate [3]. The module could perform the docking for distances up to 30 cm, and for angular displacements up to 30°.

3.7 Swarm-Bot

In swarm-bot [17, 18, 54, 55], the basic modules are called *s-bots*. The s-bot's traction system consists of a combination of tracks and two external wheels, called *treels*. The s-bot has two grippers, one is mounted on an elevation arm, the other is mounted on a flexible arm (not part of the module shown in the figure). The s-bot can receive connections on more than two thirds of its perimeter. The mechanical design of both the grippers and the connection ring helps the s-bots to passively align during the grasping phase. For the purpose of inter-module communication, the s-bot has eight RGB LEDs. The s-bot is equipped with a variety of sensors, including 19 proximity sensors, 4 optical barriers integrated in the two grippers, a VGA omni-directional camera, and 4 omni-directional microphones.

Groß and Dorigo [37] showed that self-assembly can offer *adaptive value* to groups of simulated s-bots that compete in an artificial evolution based on their fitness in group transport. Using a similar approach, Trianni *et al.* [76, 77] let groups of simulated s-bots display context-dependent switches from separate to assembled states and vice versa. Groß and Dorigo [35,38] evolved a neural network for self-assembly and transferred it from simulation to the real s-bots. The modules were manually programmed to signal their assembled or not assembled state. The performance of the system was systematically assessed under a variety of conditions [36]. In 100% of 220 cases, a single module, controlled to connect with a non-moving seed object (e.g., a stationary teammate), successfully connected. In 98% of 204 cases, a module, engaged in a group experiment (with one seed object and six s-bots in total), successfully connected. Self-assembly was also systematically examined on different types of rough terrain, all unnavigable for most standard wheeled robots of a similar size. The system performance scaled well with the number of modules as experimentally verified with groups of 16 physical modules and up to 100 modules in simulation. Given a high density of modules in the environment, it was shown in simulation that (i) the likelihood of individual modules to successfully connect to a growing entity remains high regardless of the size of the group, (ii) the mean time until a module connects to a growing entity increases sub-linearly with the group size.

The neural-network based controller was applied in a range of more complex scenarios. Groß *et al.* [35, 36] report on an experiment demonstrating the ability of seven s-bots to make use of self-assembly in order to cross a hole that cannot be overcome by less than three s-bots (whether assembled or not). O'Grady *et al.* [62] conducted a systematic experiment with three physical s-bots showing that s-bots can benefit from making adaptive use of self-assembly in a concrete task—

phototaxis in an uneven terrain. If possible, the s-bots navigated to the light source independently. If, however, the terrain proved too difficult for a single s-bot, the group self-assembled into a larger entity and collectively navigated to the light source. Another systematic experiment with six physical s-bots confirmed the use of self-assembly in the transport of a heavy object [41, 77]. Due to the limited surface of the transported object, pushing behaviors with more than two s-bots were ineffective. Due to frictional forces, the object required the cooperative effort of four or more s-bots to be moved. By using the object as a seed for self-assembly, the s-bots organized into modular entities of up to four s-bots each, that pulled the object to the target zone. Nouyan *et al.* [61] integrated this self-assembly and transport strategy in the broader context of prey search and retrieval.

3.8 Molecubes

Molecubes [58] is a homogeneous, lattice-based reconfigurable robot. The basic component module is a 10-cm cube. Each half of it can swivel relative to the other half. Each half can bind with one additional module by using electromagnets. Molecubes are powered through a baseplate and transfer data and power through their faces.

Mytilinaios *et al.* [58] investigated the use of artificial evolution to design self-replicating morphologies in a 2-D simulation environment. Zykov *et al.* [95] demonstrated (with the physical system) the self-replication of a 4-module entity provided with an ordered supply of additional modules. The system executed a predetermined sequence of actions. To confirm a successful binding among modules, communication was employed.

3.9 M-TRAN

M-TRAN [49, 57, 92] is a homogeneous modular robotic system that implements features of both chain-based and lattice-based reconfigurable systems. Each module comprises two semicylindrical blocks and a link connecting them. The blocks can rotate through a +/-90 degrees range around two parallel axes. One block of the module has three active surfaces for connecting, the other block has three passive ones.

Recently, the docking of a mobile modular robot with a stationary modular robot has been demonstrated with the M-TRAN III platform [48]. The docking was supported by sensory feedback from a dedicated camera module mounted on the stationary robot. Both image processing and control were performed on an external PC that communicated wirelessly with the modules. To achieve an accurate alignment in the final approach phase, the stationary robot clutched the connecting module of the approaching robot. The procedure proved successful for a variety of initial positions and orientations. Moreover, an integrated sequence comprising both self-assembly and self-reconfiguration was demonstrated [48]. Thereby, the entity that assembled changed shape by having modules move within its structure.

4 Taxonomy and Design Principles

In the following, we classify the information gathered in Sections 2 and 3 to help understand the relations among the different systems and to extract some underlying design principles. The section is organized into four parts with focus respectively on physical and electrical design characteristics, outcome and analysis of self-assembly experimentation, process control, and functionality.

4.1 Physical and Electrical Design Characteristics

In total, we have identified 22 different modular systems capable of self-assembling at the macroscopic scale. The appendix of this paper details the physical and electrical characteristics of the modules, including their size, weight, number of degrees of freedom (DOF), binding mechanism, as well as on-board equipment such as batteries, processors, sensors, and communication devices.

Overall, a diverse set of systems has been implemented, with modules ranging from a few centimeters to half a meter, and from 3 to 11000 gram. The design of a module layout is a highly sophisticated task. Typically, it incorporates an enormous amount of human intelligence. Automated design procedures [4, 53] have not yet been investigated in much detail.

Most systems are homogeneous, that is, all modules are identical in design. Modules of distinct types (if any) typically are complementary in terms of their binding mechanisms or functionalities. All systems use only a few distinct types of modules. This could help the fabrication of large quantities of modules. In most systems, however, fabrication still requires a considerable amount of human intervention.

The modules implement a wide range of binding mechanisms, making use of mechanics (with active or passive inter-locking), magnetism, impulse, friction, and pressure. In all systems, the binding mechanism imposes limits on the relative positions under which modules can bind to each other. It also imposes limits on the forces that can be transmitted between assembled modules.

Communication can take place in two distinct situations: between separate modules or modular entities, and within a modular entity. Communication between separate entities (if any) is local unless dedicated global communication channels are available. Communication within a modular entity can take place through serial or parallel links among all the connected modules.

4.1.1 Systems with Externally Propelled Components

In systems with externally propelled components, modules encounter each other at random. The modules are designed to operate in a rather limited range of (potentially unstructured) environments. The environment imposes constraints on the design; for instance, a module's motion can be affected by its buoyant, frictional, and gravitational forces. Some researchers report difficulties in implementing random motion without any bias in direction [5, 79].

In the systems of Griffith *et al.* and Bishop *et al.*, modules are equipped with on-board batteries. Therefore, in principle, any two modules can bind and communicate with each other upon encounter. In White *et al.*'s systems, a seed module has a dedicated link to an external power supply. Modules that bind with the seed structure receive power through the connection link.

Computing requirements for externally propelled modules are relatively low: in all systems we identified, modules can bind passively upon collision, and if any computation is necessary, it reflects the decision whether to stay assembled or not.

4.1.2 Systems with Self-Propelled Components

At the level of individual modules, propulsion can be realized with a differential drive, which provides good steering abilities on flat terrain. Tracks on the other hand allow for good all-terrain navigation. Modules of swarm-bot combine these two locomotion mechanisms to achieve good mobility on both flat and rough terrain. At the level of modular entities, propulsion requires more elaborate strategies. This is merely due to the high number of DOF that needs to be controlled in a coordinated and often distributed manner, and to the imprecision in actuation that results in positional errors, which increase with the number of elements in sequence.

In most systems with self-propelled modular entities, the latter can change shape by having modules move within their entity. This capacity is called *shape-change*—a special case of self-reconfiguration—and is typically performed very well by modular reconfigurable robots, such as PolyBot, CONRO, Molecubes, and M-TRAN. Modules of these systems could assemble an arbitrary initial structure, and subsequently customize it by shape-changing.

Modules (in particular, those of modular reconfigurable robots) have a high power consumption, which limits their lifetime without external power supply. They typically (i) perceive each other and/or the environment, and (ii) act to selectively encounter each other. This can put great demands on a module's design. In fact, many problems encountered in the design of self-assembling systems are due to shortcomings in the underlying hardware, that is, the modules' actuation [23, 44, 60], perception [11, 44, 56, 91, 95], and computational resources [3, 11, 44, 56].

Table 1: Self-assembly and its function as either demonstrated (D:N) or systematically verified in repeated trials (S:N); only systems with externally propelled components. N denotes the maximum number of separate and discrete components that self-assembled into a single entity. For details see text.

Self-Assembly System	Environment	States	Seed Entity	Autonomy	Constraints	Function
EXTERNALLY PROPELLED COMPONENTS						
Penrose & Penrose [65]	1-D	✓	✓	✓	-	1-bit replication (D:2)
Hosokawa *et al.* [45]	2-D	-[a]	-	✓	-	formation (S:6)
Breivik [9]	2-D (fluid)	✓	-	-	regulation by environment	growth & replication (D:$\geq$ 16)
White *et al.* [80] (first system)	2-D	-	✓	-	-	growth (S:2)
	2-D	✓	✓	-	-	growth & reconfiguration (D:3)
White *et al.* [80] (second system)	2-D	✓	✓	-	-	growth & reconfiguration (D:3)
Griffith *et al.* [33, 34]	2-D	✓	✓	✓	-	growth (D:26), 5-bit replication (D:5)
White *et al.* [79] (first system)	3-D (fluid)	✓	✓	-	-	growth & reconfiguration (S:2)
White *et al.* [79] (second system)	3-D (fluid)	✓	✓	-	-	growth & reconfiguration (D:2)
Bishop *et al.* [5]	2-D	✓	-	✓	-	formation (D:6)
Bhalla & Bentley [4]	2-D	-	-	✓	-	formation (D:10)

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[a] The authors discuss a second design in which modules can be in two distinct states, see text.

Table 2: Self-assembly and its function as either demonstrated (D:N) or systematically verified in repeated trials (S:N); only systems with self-propelled components. N denotes the maximum number of separate and discrete components that self-assembled into a single entity. For details see text.

Self-Assembly System	Environment	States	Seed Entity	Autonomy	Constraints	Function
			SELF-PROPELLED COMPONENTS			
RSD I [46]	1-D (loop & branches)	✓	✓	-	regulation by environment	0-bit replication (D:2)
CEBOT, Mark II [26]	2-D	✓	✓	-	-	growth (D:2)
CEBOT, Mark III [29]	2-D	✓	✓	-	-	growth (D:2)
CEBOT, Mark IV [30]	2-D	✓	✓	-	-	growth (D:2)
PolyBot, G2 [91]	2-D	✓	✓	-	pre-defined positions	growth (D:2)
PolyBot, G3 [86, 91]	3-D[a]	✓	✓	-	pre-defined positions	growth (D:2)
CONRO [68]	2-D	✓	-	-[b]	limited approaching angle	growth (S:2)
SMC [40, 84, 85]	2-D	-	✓	✓	pre-defined positions, synchronized execution	task-oriented reconfiguration (D:4)[c]
	2-D	✓	✓	-[b]	limited approaching angle	growth (S:2, D:4)
Bererton & Khosla [3]	2-D	✓	✓	-	limited approaching angle	sub-module repair (S:2)
Swarm-bot [36, 41, 62]	2-D (flat & rough)	✓	✓	✓	-	grow (S:16), task-oriented growth (D:7, S:3, S:4)
Molecubes [58, 95]	3-D (lattice)	-	✓	-	pre-defined positions	growth & 0-bit replication (D:4)
M-TRAN III [48]	2-D	✓	✓	-	limited approaching angle	growth & reconfiguration (S:2)

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[a] Experiments were conducted in the horizontal and vertical plane.

[b] During the experimentation, the modules were tethered to a power supply.

[c] A seed object composed of one parent module and three child modules disassembles and re-assembles. For details see Section 3.5.

4.2 Outcome and Analysis of Self-Assembly Experimentation

At present, self-assembly of macroscopic components has been demonstrated for 22 different systems. Tables 1 and 2 provide an overview of the experiments that were performed respectively with systems of externally propelled components and with systems of self-propelled components. Details on the experimental setup and results can be obtained from the references listed in the first column of the tables. The second column refers to the figure that shows component modules of the corresponding system.

Most of the experiments were carried out in simple environments in which motion was restricted to 1-D, 2-D, or a lattice structure (see third column). The systems of White *et al.* [79], PolyBot [86], and swarm-bot represent the first attempts to study self-assembly in more complex situations, such as 3-D environments, high-density environments, and rough terrains.

Most experiments were conducted as proofs of concept. While the number of components has been large in simulation, physical systems rarely comprised more than 50 modules, and typically no more than two components self-assembled into a same entity. For 8 out of 22 systems, the self-assembly process was systematically examined using quantitative performance measures and performing multiple trials. To the best of our knowledge, Hosokawa *et al.*'s system and swarm-bot are the only systems for which self-assembly of more than two discrete components has been systematically examined. Hosokawa *et al.* analyzed the process dynamics with focus on the yield of desired products (with six discrete components per entity). In swarm-bots, the analysis addressed the reliability and speed by which individual modules connect into single entities, as well as the additional capabilities and functions such process may provide (with up to 16 discrete components per entity).

4.3 Process Control

The process of self-assembly is governed by the modules' way to encounter each other and by the spatially anisotropic binding preferences. In relatively simple systems, modules are externally propelled and have static binding preferences. This is the case for the systems of Hosokawa *et al.* and Bhalla & Bentley. In all other systems, a module's motion and/or binding preferences can depend on its state (see Column 4 of Tables 1 and 2). The state can change in response to interactions with other modules and/or the environment. In the system of Penrose, for instance, a module's state changes by mechanical interactions with other modules. In the system of Breivik, the state is affected also by the temperature of the environment. In swarm-bot, each module broadcasts its connection state to modules in its vicinity.

In 17 out of 22 systems, self-assembly is seeded by a dedicated component (see Column 5 of Tables 1 and 2). All additional products are formed by having components interact with the seed entity and/or the products of such interactions. The seed can be a single module or a modular entity; it can be static or mobile. Typically, the seed is explicitly defined by the experimenter. However, systems can also choose autonomously the components by which to seed the process [62]. Among systems with self-propelled components, only CONRO demonstrated self-assembly without any seed component.

Seven out of 22 systems were autonomous in perception, control, action, and power (see Column 6 of Tables 1 and 2).[1] In most systems, each module executes a deterministic finite state machine. The logic can be coded in hardware, as in the systems of Penrose *et al.* and Breivik, or in software, as in all other state-based systems. In Bishop *et al.*'s system, for instance, each module executes a program that interprets a graph grammar defining state-dependent binding preferences. For swarm-bot and Molecubes, evolutionary algorithms have been applied to automate the control design. Attempts to port a controller from one physical system to another are still rare and typically require the platforms to share some common properties [40].

In some systems self-assembly was reported to take place under constrained conditions (see Column 7 of Tables 1 and 2). Examples are a priori assumptions on the components' initial spatial arrangement and components with knowledge of their own relative starting positions. Clearly, it

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[1] External agitation apparatuses (if any) are considered as "natural" part of the environment.

is more demanding to realize self-assembly in a system of disordered components that lack any knowledge about their relative positions.

4.4 Functionality

The last column of Tables 1 and 2 details the basic function of the system that was either **d**emonstrated (D:N), or **s**ystematically verified in repeated trials (S:N). Thereby, N indicates the maximum number of separate and discrete components that self-assembled into a single entity. The purpose of self-assembling can be manifold:

- **growth**: increase of the number and/or type of modules in an entity. To some extent, this capacity is available in all self-assembling system. However, the capacity to grow can be limited by the design. In swarm-bot, mobile modules have shown to form growing entities that display additional capabilities and functions. Examples are (i) transport of objects too heavy for manipulation by the modules when separate, and (ii) locomotion over terrains unnavigable for individual modules.
- **self-reconfiguration**: change of an existing entities morphology. This capability can be achieved by disassembling and re-assembling (e.g., as in SMC), or by *shape-change* (e.g., as in M-TRAN). For SMC it was shown that, by disassembling and re-assembling, a modular entity can solve a problem better than it could in its original configuration.
- **formation**: production of one or more objects of a pre-defined size and structure. In some systems, the module layout is specifically designed for the assembly of desired objects. In other systems, the final product is flexible, as it can be defined by re-programming each module (e.g., to execute a different graph grammar).
- **template replication**: replication of a template by producing objects of identical size, structure, and state. Templates for replication can be pre-assembled, specific seed entities (e.g., as in RSD I and Molecubes), pre-assembled seed entities with information in the modules' state (e.g., as in Penrose's and Griffith *et al.*'s system), or products of the self-assembly process (e.g., as in Breivik's system).
- **self-repair**: replacement of an entities' defective modules with its redundant modules or other modules available in the environment.

5 Future Directions

We believe that a unifying theory would greatly support the design and study of self-assembling systems. In particular, it could help develop an understanding of the relationship between the logic of components on one side, and the (dynamic or static) patterns and structures on the other side. In most studies we presented, the authors could predict the structures in which the components self-assembled. If underlying generic principles would be uncovered, rules could be generated for expressing arbitrary patterns, structures, or functions. Some promising first steps have already been taken by the development of compilers [47, 50, 59] that take as input a desired pattern or structure and generate a suitable rule set for a system of simplistic components. However, current compilers are limited in the range of patterns and structures they can process. Rothemund [67] views structures as computations; in fact, all assembled structures can be interpreted as computations, and vice versa. Theory might help to predict the range of structures (i.e., computations) a given system can produce, as well as the time complexity to do so.

Macroscopic self-assembly is of wide interest throughout science and technology. Macroscopic systems are increasingly viewed as viable models for the study of processes at any scale [81]. Table 3 gives a broad flavor of potential applications within technical and scientific areas.

One trend in the design of systems is miniaturization. Among the different designs considered, externally propelled components appear most suited for this purpose as they do not necessarily

Table 3: Technological and scientific areas that are likely to benefit from the study of macroscopic self-assembly.

Scale	Enhancing Technology	Understanding Nature
macroscopic	all-terrain navigation [44] educational tools search & rescue [54] self-construction [72] self-repair devices [2] space robotics [71] under water robotics [78]	plant growth social insects [74]
mesoscopic	3-D displays [31] computation [67] drug delivery systems manufacturing [20] microelectronics [32] smart materials	origin of life [16] self-replication [33]

require complex computation, actuators, and sensors. Future designs could greatly benefit from bio-mimetics. Artificial components (or assemblies of those) could, similar to living entities, absorb energy from their environment (instead of using dedicated power supplies). A range of studies has addressed the design of millimeter-scale components for the formation of 2-D arrays, 3-D regular lattices, helixes, and electrical networks [7, 8, 32, 73, 75]. Components at this scale can exhibit a similar range of physical interactions as components at the micro- or even nano-scale (e.g., capillary forces, hydrodynamic shear, and minimization of interfacial free energy). One challenge is the transfer of knowledge gained with macroscopic systems to the design of mesoscopic systems in order to obtain structures that provide function and can cope with changes in the environment (e.g., smart materials).

Systems with self-propelled components have great prospects in autonomous robotics. Autonomous missions, such as the exploration of the surface of another planet, impose high demands on the flexibility and robustness of a system. From today's technology perspective, the component modules of most systems lack advanced on-board computing resources, on-board sensors, or communication abilities. These shortcomings limit the practical use of current systems for complex missions in unstructured terrains.

Another promising direction is the study of novel designs of self-assembling systems. Hybrid systems, for instance, could comprise externally propelled components with actuated degrees of freedom. Components could passively float in an agitated fluid and, upon random encounter, bind to each other to form a structure that changes morphology and/or manipulates the environment. Simulations indicate potential use of such systems in manufacturing [20]. Innovative designs can also be observed in nature. Some plants grow in groups and have their roots and/or branches gradually inter-twisted. Such self-assembly relies on developmental processes of the participating components. Connectivity potentially provides adaptive value, for instance, to survive harsh condition. Certainly, many more self-assembly processes can be found in nature, and might inspire next generation designs.

6 Conclusions

During the last 50 years, a variety of systems were designed displaying self-assembly of components at the macroscopic scale. In this paper, we presented an overview of this research. We compared

22 systems with regard to (i) the physical and electrical design characteristics of the component modules, (ii) the outcome and analysis of self-assembly experimentation, (iii) the mechanisms that control the process of self-assembly, and (iv) the functionality that is provided. Thereby, we identified principles that are common to the design of such systems. Finally, we indicated potential directions for future research.

Overall, an impressive diversity of systems have been realized, acting in various types of environments. The systems provide a range of elementary functions such as growth, self-reconfiguration, formation, template replication, and self-repair. To help the reader in further assessing the current state of the art, we have collected video recordings and additional material, that are available in [39].

Clearly, studies on macroscopic self-assembly are of potential value for a range of fields, including biology, chemistry, manufacturing, material science, microelectronics, physics, robotics, and sociology. The expertise and variety of view points in these fields hold great potential to be explored for the design and study of artificial and natural self-assembling systems.

Appendix

Tables 4 to 7 summarize the physical and electrical characteristics of the modules of the 22 systems discussed in this paper. Entries of the first columns identify each system by its name, if any, or (otherwise) by the name of the authors (abbreviated, if more than two) that reported in the literature on the system's implementation. The second column refers to the figure that shows component modules of the corresponding system. Table entries that are *italicized* have been obtained directly by contacting one of the authors of the corresponding study. All other entries have been obtained from the references specified in the first columns.

All tables list only the characteristics of standard modules. Additional modules might have been designed for special purposes and could be complementary in functionality. Tables 4 and 5 present respectively the physical characteristics of modules in systems with externally propelled components and in systems with self-propelled components. Entries of the third column indicate whether or not a system is composed of homogeneous modules. The dimensions (in cm) listed in the fourth column specify the length, width, and height of a module excluding its binding mechanism. Typically, it is this measure that is reported. Entries of the fifth column specify a module's weight (in g). For systems in which fluid can enter the module, the module's net weight is reported. The sixth column details a module's number of degrees of freedom (DOF). DOF with two displacements only (e.g., a latch) are referred to as *binary*, all others as *full*. The last column details the principle of the module's binding mechanism. Tables 6 and 7 present respectively the electrical characteristics of modules in systems with externally propelled components and in systems with self-propelled components. Entries of the third column specify whether a module has on-board power or not. The fourth column lists the available on-board processing resources. It is noted if a module was designed for being controlled remotely. The fifth column summarizes a module's on-board sensors. These do not include proprioceptive sensors, nor those sensors integrated only on non-standard modules. The last column lists a module's devices for inter-module communication. This comprises communication in both the assembled and the separate state.

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Table 4: Physical characteristics of modules for self-assembly (only systems with externally propelled components). For details see text.

Self-Assembly System	Single Module Type	Dimensions (L/W/H in cm)	Weight (in g)	DOF (Full/Binary)	Binding Mechanism
EXTERNALLY PROPELLED COMPONENTS					
Penrose & Penrose [65]	-	not specified	not specified	0/0	mechanical interlocking upon collision
Hosokawa *et al.* [45]	✓	2.5/2.2/1.0	3	0/0	permanent magnets
Breivik [9]	-	*6.0/4.0/2.0*	not specified	0/0	permanent magnets[a]
White *et al.* [80] (first system)	✓	*6.5/6.5/6.5*	*165*	0/4	electromagnets
White *et al.* [80] (second system)	✓	*6.5/6.5/6.5*	*165*	0/4	swiveling permanent magnets
Griffith *et al.* [33, 34]	✓	5.0/5.0/1.5	26	0/2	mechanical latch, regulated electromagnetically
White *et al.* [79] (first system)	✓	10 /10 /10	*895*	0/6	electromagnets
White *et al.* [79] (second system)	✓	*13 /13 /13*	*1480*	0/6	pressure of fluid flow, regulated by valves
Bishop *et al.* [5]	✓	12 /10 /4.2	*110*	0/3	swiveling permanent magnets
Bhalla & Bentley [4]	-	module specific	module specific	0/0	permanent magnets

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[a] The ambient temperature temporarily exceeds the Curie points (i.e., the temperature above which permanent magnets lose their characteristic ferromagnetic ability).

Table 5: Physical characteristics of modules for self-assembly (only systems with self-propelled components). For details see text.

Self-Assembly System	Single Module Type	Dimensions (L/W/H in cm)	Weight (in g)	DOF (Full/Binary)	Binding Mechanism
Self-Propelled Components					
RSD I [46]	-	14 /3.6/11	not specified	1/ 0	impulse & friction
CEBOT, Mark II [28, pp. 50–56, 151–156], [21]	-	13 /18 /9.0	2700	2-4/ 0	actuated mechanical hook
CEBOT, Mark III [29]	✓	not specified	not specified	0/ 9	mechanical pin/hole & SMA
CEBOT, Mark IV [27, 30]	-	19 /11 /24	4100	2-3/ 0	actuated mechanical hook
PolyBot, G2 [88, 91]	-	6.0/7.0/11	416	1/ 2	mechanical pin/hole & SMA
PolyBot, G3 [89, 91, 94]	✓	5.0/5.0/4.5	*200*	1/ 2	mechanical pin/hole & SMA
CONRO [13, 63, 68]	✓	11 /4.4/4.5	114	2/ 1	mechanical pin/hole & SMA
SMC [15, 40, 85]	-	26 /26 /51	11000	5/ 0	actuated mechanical hook
Bererton & Khosla [2, 3]	✓	10 /6.0/8.0	≈*250*	3/ 0	mechanical pin/hole
Swarm-bot [54, 55]	✓	12 /12 /19	700	9/ 0	actuated mechanical hook
Molecubes [58, 95]	✓	10 /10 /10	*650*	1/ *2*	electromagnets
M-TRAN III [48]	✓	13 /6.5/6.5	420	2/ 3	actuated mechanical hooks

Table 6: Electrical characteristics of modules for self-assembly (only systems with externally propelled components). For details see text.

Self-Assembly System	Batteries	Processor(s)	Sensors	Communication Devices
EXTERNALLY PROPELLED COMPONENTS				
Penrose & Penrose [65]	-	-	-	-
Hosokawa *et al.* [45]	-	-	-	-
Breivik [9]	-	-	-	-
White *et al.* [80] (first system)	-	8-bit Basic Stamp II-*SX, 50 MHz*	-	serial link between connected modules
White *et al.* [80] (second system)	-	8-bit Basic Stamp II, *20 MHz*	-	serial link between connected modules
Griffith *et al.* [33, 34]	✓	8-bit ATmega8, 8 MHz	-	4 wireless electromagnetic local transmitters, 1-10mm
White *et al.* [79] (first system)	-	8-bit Basic Stamp II-*SX, 50 MHz*	-	*serial link between connected modules*
White *et al.* [79] (second system)	-	*8-bit Basic Stamp II-SX, 50 MHz*	-	*serial link between connected modules*
Bishop *et al.* [5]	✓	8-bit PIC18F242, 3.6 MHz	3 infrared detectors	3 infrared emitters
Bhalla & Bentley [4]	-	-	-	-

Table 7: Electrical characteristics of modules for self-assembly (only systems with self-propelled components). For details see text.

Self-Assembly System	Batteries	Processor(s)	Sensors	Communication Devices
Self-Propelled Components				
RSD I [46]	-	relay (1 head, 2 tail)	bump switch (0 head, 3 tail)	parallel link between connected modules
CEBOT, Mark II [28, pp. 50–56, 151–156], [21]	-	sub CPU (+ main CPU off-board)	4 infrared detectors (3 rigid, 1 rotational), 3 ultrasonic distance (1Tx and 2Rx)	9 infrared emitters (8 rigid, 1 rotational), parallel link between connected modules
CEBOT, Mark III [29]	-	sub CPU (+ main CPU off-board)	9 infrared detectors, 6 ultrasonic distance (3Tx and 3Rx)	9 infrared emitters, link between connected modules
CEBOT, Mark IV [27,30]	-	16-bit 8086, 5-10 MHz	2 infrared detectors	2 infrared emitters, wireless (RS-232C)
PolyBot, G2 [88,91]	-	32-bit PowerPC555 (MPC555), 40 MHz	4 infrared detectors	8 infrared emitters, 2 CANbus
PolyBot, G3 [89,91,94]	-	*32-bit PowerPC555 (MPC555), 40 MHz*	8 infrared detectors, 2 2-axis inclinometers, 8 *1-axis* force	8 infrared emitters, *2 CANbus*
CONRO [13,63,68]	✓	8-bit Basic Stamp II-SX, 50 MHz	4 infrared detectors	4 infrared emitters
SMC [15,40,85]	✓	32-bit Pentium MMX, 233 MHz	color camera (2 per parent: *640x416*, 2-3 per child: *320x240*), 1-axis force	*Wi-Fi*
Bererton & Khosla [2,3]	✓	8-bit PIC16C73A, 20 MHz + off-board	B&W camera (320x240), bump switch	wireless (RF)
Swarm-bot [54,55]	✓	32-bit XScale, 400 MHz + 13 8-bit PIC16F876/7, 20 MHz	19 infrared proximity, color camera (640x480, omnidirectional), 2-axis force, torque, 4 microphones, 8 light, 3-axis inclinometer, 2 humidity, 4 light barriers	8 RGB LEDs changing body color, 2 speakers, Wi-Fi
Molecubes [58,95]	-	*8-bit Basic Stamp II-SX, 50 MHz*	-	serial link between connected modules (*shared bus*)
M-TRAN III [48]	✓	*32-bit SH7047, 40 MHz, 3 16-bit H8, 16MHz* + off-board	*13* infrared detectors, *3-axis inclinometer*	*13* infrared emitters, *CANbus*, wireless (BlueTooth)

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References

[1] C. Anderson, G. Theraulaz, and J.-L. Deneubourg. Self-assemblages in insect societies. *Insectes Soc.*, 49(2):99–110, 2002.

[2] C. Bererton and P. K. Khosla. Towards a team of robots with reconfiguration and repair capabilities. In *Proc. of the 2001 IEEE Int. Conf. on Robotics and Automation*, volume 3, pages 2923–2928. IEEE Computer Society Press, Los Alamitos, CA, 2001.

[3] C. Bererton and P. K. Khosla. Towards a team of robots with repair capabilities: a visual docking system. In *Proc. of the* 7^{th} *Int. Symp. on Experimental Robotics*, volume 271 of *Lecture Notes in Control and Information Sciences*, pages 333–342. Springer Verlag, Berlin, Germany, 2001.

[4] N. Bhalla and P. J. Bentley. Working towards self-assembling robots at all scales. In *Proc. of the 3rd Int. Conf. on Autonomous Robots and Agents*, pages 617–622, Massey University, New Zealand, 2006.

[5] J. Bishop, S. Burden, E. Klavins, R. Kreisberg, W. Malone, N. Napp, and T. Nguyen. Programmable parts: A demonstration of the grammatical approach to self-organization. In *Proc. of the 2005 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pages 2644–2651. IEEE Computer Society Press, Los Alamitos, CA, 2005.

[6] M. Boncheva, D. A. Bruzewicz, and G. M. Whitesides. Millimeter-scale self-assembly and its applications. *Pure Appl. Chem.*, 75(5):621–630, 2003.

[7] N. Bowden, A. Terfort, J. Carbeck, and G. M. Whitesides. Self-assembly of mesoscale objects into ordered two-dimensional arrays. *Science*, 276(5310):233–235, 1997.

[8] T. L. Breen, J. Tien, S. R. J. Oliver, T. Hadzic, and G. M. Whitesides. Design and self-assembly of open, regular, 3D mesostructures. *Science*, 284(5416):948–951, 1999.

[9] J. Breivik. Self-organization of template-replicating polymers and the spontaneous rise of genetic information. *Entropy*, 3(4):273–279, 2001.

[10] R. Brown. A brief account of microscopical observations made in the months of June, July and August, 1827, on the particles contained in the pollen of plants; and on the general existence of active molecules in organic and inorganic bodies. *Phil. Mag.*, 4:161–173, 1828.

[11] H. B. Brown Jr, J. M. V. Weghe, C. A. Bererton, and P. K. Khosla. Millibot trains for enhanced mobility. *IEEE/ASME Trans. Mechatron.*, 7(4):452–461, 2002.

[12] D. L. D. Caspar. Design principles in organized biological structures. In G. E. W. Wolstenholme and M. O'Connor, editors, *Principles of Biomolecular Organization*, pages 7–34. J. & A. Churchill Ltd., London, UK, 1966.

[13] A. Castano, A. Behar, and P. M. Will. The Conro modules for reconfigurable robots. *IEEE/ASME Trans. Mechatron.*, 7(4):403–409, 2002.

[14] A. Castano, W.-M. Shen, and P. M. Will. CONRO: Towards deployable robots with inter-robots metamorphic capabilities. *Auton. Robots*, 8(3):309–324, 2000.

[15] R. Damoto, A. Kawakami, and S. Hirose. Study of super-mechano colony: concept and basic experimental set-up. *Adv. Robot.*, 15(4):391–408, 2001.

[16] D. Deamer, S. Singaram, S. Rajamani, V. Kompanichenko, and S. Guggenheim. Self-assembly processes in the prebiotic environment. *Phil. Trans. R. Soc. B*, 361(1474):1809–1818, 2006.

[17] M. Dorigo, V. Trianni, E. Şahin, R. Groß, T. H. Labella, G. Baldassarre, S. Nolfi, J.-L. Deneubourg, F. Mondada, D. Floreano, and L. M. Gambardella. Evolving self-organizing behaviors for a *Swarm-Bot*. *Auton. Robots*, 17(2–3):223–245, 2004.

[18] M. Dorigo, E. Tuci, V. Trianni, R. Groß, S. Nouyan, C. Ampatzis, T. H. Labella, R. O'Grady, M. Bonani, and F. Mondada. SWARM-BOT: Design and implementation of colonies of self-assembling robots. In G. Y. Yen and D. B. Fogel, editors, *Computational Intelligence: Principles and Practice*, pages 103–135. IEEE Computer Society Press, Los Alamitos, CA, 2006.

[19] A. Einstein. Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen. *Ann. Phys.*, 17(8):549–560, 1905.

[20] R. Ewaschuk and P. D. Turney. Self-replication and self-assembly for manufacturing. *Artif. Life*, 12(3):411–433, 2006.

[21] T. Fukuda, M. Buss, H. Hosokai, and Y. Kawauchi. Cell structured robotic system CEBOT: Control, planning and communication. *Robot. Auton. Syst.*, 7(2–3):239–248, 1991.

[22] T. Fukuda and S. Nakagawa. A dynamically reconfigurable robotic system (concept of a system and optimal configurations). In *Proc. of the 1987 IEEE Int. Conf. on Industrial Electronics, Control and Instrumentation*, pages 588–595. IEEE Computer Society Press, Los Alamitos, CA, 1987.

[23] T. Fukuda and S. Nakagawa. Approach to the dynamically reconfigurable robotic system. *J. Intell. Robot. Syst.*, 1(1):55–72, 1988.

[24] T. Fukuda and S. Nakagawa. Dynamically reconfigurable robotic system. In *Proc. of the 1988 IEEE Int. Conf. on Robotics and Automation*, volume 3, pages 1581–1586. IEEE Computer Society Press, Los Alamitos, CA, 1988.

[25] T. Fukuda and S. Nakagawa. Method of autonomous approach, docking and detaching between cells for dynamically reconfigurable robotic system CEBOT. *JSME Int. J. III-VIB. C.*, 33(2):263–268, 1990.

[26] T. Fukuda, S. Nakagawa, Y. Kawauchi, and M. Buss. Self organizing robots based on cell structures—CEBOT. In *Proc. of the 1988 IEEE Int. Workshop on Intelligent Robots*, pages 145–150. IEEE Computer Society Press, Los Alamitos, CA, 1988.

[27] T. Fukuda, K. Sekiyama, T. Ueyama, and F. Arai. Efficient communication method in the cellular robotic system. In *Proc. of the 1993 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 2, pages 1091–1096. IEEE Computer Society Press, Los Alamitos, CA, 1993.

[28] T. Fukuda and T. Ueyama. *Cellular Robotics and Micro Robotic Systems.* World Scientific Publishing, London, UK, 1994.

[29] T. Fukuda, T. Ueyama, and Y. Kawauchi. Self-organization in cellular robotic system (CEBOT) for space application with knowledge allocation method. In *Proc. of the 1990 Int. Symp. on Artificial Intelligence, Robotics and Automation in Space*, pages 101–104, Kobe, Japan, 1990.

[30] T. Fukuda, T. Ueyama, and K. Sekiyama. *Artificial Intelligence in Industrial Decision Making, Control and Automation*, chapter 8. Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995.

[31] S. C. Goldstein, J. D. Campbell, and T. C. Mowry. Programmable matter. *Computer*, 38(6):99–101, 2005.

[32] D. H. Gracias, J. Tien, T. L. Breen, C. Hsu, and G. M. Whitesides. Forming electrical networks in three dimensions by self-assembly. *Science*, 289(5482):1170–1172, 2000.

[33] S. Griffith, D. Goldwater, and J. M. Jacobson. Self-replication from random parts. *Nature*, 437(7059):636, 2005.

[34] S. T. Griffith. *Growing Machines.* PhD thesis, MIT, MA, USA, September 2004.

[35] R. Groß, M. Bonani, F. Mondada, and M. Dorigo. Autonomous self-assembly in a swarm-bot. In *Proc. of the* 3^{rd} *Int. Symp. on Autonomous Minirobots for Research and Edutainment (AMiRE 2005)*, pages 314–322. Springer Verlag, Berlin, Germany, 2006.

[36] R. Groß, M. Bonani, F. Mondada, and M. Dorigo. Autonomous self-assembly in swarm-bots. *IEEE Trans. Robot.*, 22(6):1115–1130, 2006.

[37] R. Groß and M. Dorigo. Evolving a cooperative transport behavior for two simple robots. In *Artificial Evolution – 6th Int. Conf., Evolution Artificielle (EA 2003)*, volume 2936 of *Lecture Notes in Computer Science*, pages 305–317. Springer Verlag, Berlin, Germany, 2004.

[38] R. Groß and M. Dorigo. Group transport of an object to a target that only some group members may sense. In *Proc. of the* 8^{th} *Int. Conf. on Parallel Problem Solving from Nature (PPSN VIII)*, volume 3242 of *Lecture Notes in Computer Sciences*, pages 852–861. Springer Verlag, Berlin, Germany, 2004.

[39] R. Groß and M. Dorigo. Collection of videos of self-assembling systems. `http://iridia.ulb.ac.be/supp/IridiaSupp2007-004/`, 2007.

[40] R. Groß, M. Dorigo, and M. Yamakita. Self-assembly of mobile robots—from swarm-bot to super-mechano colony. In *Proc. of the* 9^{th} *Int. Conf. on Intelligent Autonomous Systems*, pages 487–496. IOS Press, Amsterdam, The Netherlands, 2006.

[41] R. Groß, E. Tuci, F. Mondada, and M. Dorigo. Object transport by modular robots that self-assemble. In *Proc. of the 2006 IEEE Int. Conf. on Robotics and Automation*, pages 2558–2564. IEEE Computer Society Press, Los Alamitos, CA, 2006.

[42] S. Hirose. Super mechano-system: New perspective for versatile robotic system. In *Proc. of the* 7^{th} *Int. Symp. on Experimental Robotics*, volume 271 of *Lecture Notes in Control and Information Sciences*, pages 249–258. Springer Verlag, Berlin, Germany, 2001.

[43] S. Hirose, R. Damoto, and A. Kawakami. Study of super-mechano-colony (concept and basic experimental setup). In *Proc. of the 2000 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 3, pages 1664–1669. IEEE Computer Society Press, Los Alamitos, CA, 2000.

[44] S. Hirose, T. Shirasu, and E. F. Fukushima. Proposal for cooperative robot "Gunryu" composed of autonomous segments. *Robot. Auton. Syst.*, 17:107–118, 1996.

[45] K. Hosokawa, I. Shimoyama, and H. Miura. Dynamics of self-assembling systems: Analogy with chemical kinetics. *Artif. Life*, 1(4):413–427, 1995.

[46] H. Jacobson. On models of reproduction. *Am. Sci.*, 46:255–284, September 1958.

[47] C. Jones and M. J. Matarić. From local to global behavior in intelligent self-assembly. In *Proc. of the 2003 IEEE Int. Conf. on Robotics and Automation*, volume 1, pages 721–726, IEEE Computer Society Press, Los Alamitos, CA, 2003.

[48] K. Kakomura, H. Kurokawa, and S. Murata. Docking experiments of a modular robot by visual feedback. In *Proc. of the 2006 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*. IEEE Computer Society Press, Los Alamitos, CA, 2006.

[49] A. Kamimura, H. Kurokawa, E. Yoshida, S. Murata, K. Tomita, and S. Kokaji. Automatic locomotion design and experiments for a modular robotic system. *IEEE/ASME Trans. Mechatron.*, 10(3):314–325, 2005.

[50] E. Klavins, R. Ghrist, and D. Lipsky. A grammatical approach to self-organizing robotic systems. *IEEE Trans. Automat. Contr.*, 51(6):949–962, 2006.

[51] A. Lioni and J.-L. Deneubourg. Collective decision through self-assembling. *Naturwissenschaften*, 91(5):237–241, 2004.

[52] A. Lioni, C. Sauwens, G. Theraulaz, and J.-L. Deneubourg. Chain formation in *Œcophylla longinoda*. *J. Insect Behav.*, 14(5):679–696, 2001.

[53] H. Lipson and J. B. Pollack. Automatic design and manufacture of robotic lifeforms. *Nature*, 406(6799):974–978, 2000.

[54] F. Mondada, L. M. Gambardella, D. Floreano, S. Nolfi, J.-L. Deneubourg, and M. Dorigo. SWARM-BOTS: Physical interactions in collective robotics. *IEEE Robot. Automat. Mag.*, 12(2):21–28, 2005.

[55] F. Mondada, A. Guignard, M. Bonani, D. Bär, M. Lauria, and D. Floreano. SWARM-BOT: From concept to implementation. In *Proc. of the 2003 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 2, pages 1626–1631. IEEE Computer Society Press, Los Alamitos, CA, 2003.

[56] K. Motomura, A. Kawakami, and S. Hirose. Development of arm equipped single wheel rover: Effective arm-posture-based steering method. *Auton. Robots*, 18(2):215–229, 2005.

[57] S. Murata, E. Yoshida, A. Kamimura, H. Kurokawa, K. Tomita, and S. Kokaji. M-TRAN: Self-reconfigurable modular robotic system. *IEEE/ASME Trans. Mechatron.*, 7(4):431–441, 2002.

[58] E. Mytilinaios, M. Desnoyer, D. Marcus, and H. Lipson. Designed and evolved blueprints for physical self-replicating machines. In *Proc. of the* 9th *Int. Conf. on the Simulation and Synthesis of Living Systems (Artificial Life IX)*, pages 15–20. MIT Press, Cambridge, MA, 2004.

[59] R. Nagpal. Self-organizing shape and pattern: From cells to robots. *IEEE Intell. Syst.*, 21(2):50–53, 2006.

[60] J. Nembrini, N. Reeves, E. Poncet, A. Martinoli, and A. Winfield. Mascarillons: flying swarm intelligence for architectural research. In *Proc. of the 2005 IEEE Swarm Intelligence Symp.*, pages 225–232. IEEE Computer Society Press, Los Alamitos, CA, 2005.

[61] S. Nouyan, R. Groß, M. Bonani, F. Mondada, and M. Dorigo. Group transport along a robot chain in a self-organised robot colony. In *Proc. of the* 9th *Int. Conf. on Intelligent Autonomous Systems*, pages 433–442. IOS Press, Amsterdam, The Netherlands, 2006.

[62] R. O'Grady, R. Groß, M. Bonani, F. Mondada, and M. Dorigo. Self-assembly on demand in a group of physical autonomous mobile robots navigating rough terrain. In *Proc. of the* 8th *European Conf. on Artificial Life*, volume 3630 of *Lecture Notes in Artificial Intelligence*, pages 272–281. Springer Verlag, Berlin, Germany, 2005.

[63] K. Payne, B. Salemi, P. Will, and W.-M. Shen. Sensor-based distributed control for chain-typed self-reconfiguration. In *Proc. of the 2004 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, volume 2, pages 2074–2080. IEEE Computer Society Press, Los Alamitos, CA, 2004.

[64] L. S. Penrose. Self-reproducing machines. *Sci. Am.*, 200:105–114, June 1959.

[65] L. S. Penrose and R. Penrose. A self-reproducing analogue. *Nature*, 179(4571):1183, 1957.

[66] D. Philp and J. F. Stoddart. Self-assembly in natural and unnatural systems. *Angew. Chem. Int. Edit.*, 35(11):1154–1196, 1996.

[67] P. W. K. Rothemund. From the cover: Using lateral capillary forces to compute by self-assembly. *Proc. Natl. Acad. Sci. U.S.A.*, 97(3):984–989, 2007.

[68] M. Rubenstein, K. Payne, P. Will, and W.-M. Shen. Docking among independent and autonomous CONRO self-reconfigurable robots. In *Proc. of the 2004 IEEE Int. Conf. on Robotics and Automation*, volume 3, pages 2877–2882. IEEE Computer Society Press, Los Alamitos, CA, 2004.

[69] D. Rus, Z. Butler, K. Kotay, and M. Vona. Self-reconfiguring robots. *Commun. ACM*, 45(3):39–45, 2002.

[70] A. B. Sendova-Franks and N. R. Franks. Self-assembly, self-organization and division of labour. *Phil. Trans. R. Soc. B*, 354(1388):1395–1405, 1999.

[71] W.-M. Shen, P. Will, and B. Khoshnevis. Self-assembly in space via self-reconfigurable robots. In *Proc. of the 2003 IEEE Int. Conf. on Robotics and Automation*, volume 2, pages 2516–2521. IEEE Computer Society Press, Los Alamitos, CA, 2003.

[72] K. Stoy. Using cellular automata and gradients to control self-reconfiguration. *Robot. Auton. Syst.*, 54(2):135–141, 2006.

[73] A. Terfort, N. Bowden, and G. M. Whitesides. Three-dimensional self-assembly of millimetre-scale components. *Nature*, 386(6621):162–164, 1997.

[74] G. Theraulaz, E. Bonabeau, C. Sauwens, J.-L. Deneubourg, A. Lioni, F. Libert, L. Passera, and R. Solé. Model of droplet dynamics in the argentine ant *Linepithema Humile* (Mayr). *Bull. Math. Biol.*, 63(6):1079–1093, 2001.

[75] J. Tien, T. L. Breen, and G. M. Whitesides. Crystallization of millimeter-scale objects with use of capillary forces. *J. Am. Chem. Soc.*, 120(48):12670–12671, 1998.

[76] V. Trianni, E. Tuci, and M. Dorigo. Evolving functional self-assembling in a swarm of autonomous robots. In *Proc. of the* 8^{nd} *Int. Conf. on Simulation of Adaptive Behavior*, pages 405–414. MIT Press, Cambridge, MA, 2004.

[77] E. Tuci, R. Groß, V. Trianni, M. Bonani, F. Mondada, and M. Dorigo. Cooperation through self-assembling in multi-robot systems. *ACM Transactions on Autonomous and Adaptive Systems*, 1(2):115–150, 2006.

[78] B. von Haller, A. Ijspeert, and D. Floreano. Co-evolution of structures and controllers for Neubot underwater modular robots. In *Proc. of the* 8^{th} *European Conf. on Artificial Life*, volume 3630 of *Lecture Notes in Artificial Intelligence*, pages 189–199. Springer Verlag, Berlin, Germany, 2005.

[79] P. White, V. Zykov, J. Bongard, and H. Lipson. Three dimensional stochastic reconfiguration of modular robots. In *Proc. of the 2006 Robotics: Science and Systems Conf.*, pages 161–168. MIT Press, Cambridge, MA, 2005.

[80] P. J. White, K. Kopanski, and H. Lipson. Stochastic self-reconfigurable cellular robotics. In *Proc. of the 2004 IEEE Int. Conf. on Robotics and Automation*, volume 3, pages 2888–2893. IEEE Computer Society Press, Los Alamitos, CA, 2004.

[81] G. M. Whitesides and M. Boncheva. Beyond molecules: Self-assembly of mesoscopic and macroscopic components. *Proc. Natl. Acad. Sci. U.S.A.*, 99(8):4769–4774, 2002.

[82] G. M. Whitesides and B. Grzybowski. Self-assembly at all scales. *Science*, 295(5564):2418–2421, 2002.

[83] H. V. Wilson. A new method by which sponges may be artificially reared. *Science*, 25(649):912–915, 1907.

[84] M. Yamakita. Formation control. Retrieved October 22, 2004, from `http://www.ac.ctrl.titech.ac.jp/~yamakita/coe/smc.html`.

[85] M. Yamakita, Y. Taniguchi, and Y. Shukuya. Analysis of formation control of cooperative transportation of mother ship by SMC. In *Proc. of the 2003 IEEE Int. Conf. on Robotics and Automation*, volume 1, pages 951–956. IEEE Computer Society Press, Los Alamitos, CA, 2003.

[86] M. Yim. Modular self-reconfigurable robotics: What's next? presented at the US-Korea Conf. Sci. Technol. Entrepreneurship, Durham, NC, 2004. [Online] Available: http://www.ksea.org.

[87] M. Yim, D. G. Duff, and K. D. Roufas. PolyBot: a modular reconfigurable robot. In *Proc. of the 2000 IEEE Int. Conf. on Robotics and Automation*, volume 1, pages 514–520. IEEE Computer Society Press, Los Alamitos, CA, 2000.

[88] M. Yim, D. G. Duff, and K. D. Roufas. Walk on the wild side. *IEEE Robot. Automat. Mag.*, 9(4):49–53, 2002.

[89] M. Yim, K. Roufas, D. Duff, Y. Zhang, C. Eldershaw, and S. B. Homans. Modular reconfigurable robots in space applications. *Auton. Robots*, 14(2–3):225–237, 2003.

[90] M. Yim, Y. Zhang, and D. Duff. Modular robots. *IEEE Spectr.*, 39(2):30–34, 2002.

[91] M. Yim, Y. Zhang, K. Roufas, D. Duff, and C. Eldershaw. Connecting and disconnecting for chain self-reconfiguration with PolyBot. *IEEE/ASME Trans. Mechatron.*, 7(4):442–451, 2002.

[92] E. Yoshida, S. Murata, A. Kamimura, K. Tomita, H. Kurokawa, and S. Kokaji. A self-reconfigurable modular robot: Reconfiguration and planning and experiments. *Int. J. Robot Res.*, 21(10–11):903–915, 2002.

[93] E. Yoshida, S. Murata, S. Kokaji, A. Kamimura, K. Tomita, and H. Kurokawa. Get back in shape! *IEEE Robot. Automat. Mag.*, 9(4):54–60, 2002.

[94] Y. Zhang, K. Roufas, C. Eldershaw, M. Yim, and D. Duff. Sensor computations in modular self reconfigurable robots. In *Proc. of the* 8^{th} *Int. Symp. on Experimental Robotics*, volume 5 of *Springer Tracts in Advanced Robotics*, pages 276–286. Springer Verlag, Berlin, Germany, 2003.

[95] V. Zykov, E. Mytilinaios, B. Adams, and H. Lipson. Self-reproducing machines. *Nature*, 435(7039):163–164, 2005.