Fifty Years of Self-Assembly Experimentation

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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 study of 22 such systems, exhibiting components ranging from passive mechanical parts to mobile robots. We discuss the systems with regard to physical and electrical design characteristics, outcome and analysis of self-assembly experimentation, process control, and functionality.**

I. 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 [59], 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 (a) in which separate components (physically) bind together, and (b) 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], [10], [48]. 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 [45]. Another example are ants of the species *Œcophylla longinoda* [32], [33] 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 [58], and for the regeneration of functional sponges of the species *Sycon raphanus* after a manipulative isolation of their cells [60].

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In this paper, we review fifty years of experimentation with self-assembling systems. We focus on artificial systems at the macroscopic scale. These systems consist of centimeter-sized components, which currently seem the biggest available in man-made self-assembly systems.

In total, we have identified 22 different modular systems that demonstrated self-assembly at the macroscopic scale (see Table I). In the following, we look at (a) physical and electrical design characteristics, (b) outcome and analysis of self-assembly experimentation, (c) process control, and (d) functionality.

II. PHYSICAL AND ELECTRICAL DESIGN CHARACTERISTICS

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], [34] 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 interlocking), 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.

In general, two distinct classes of self-assembling systems exist: systems in which the components (that assemble) are externally propelled, and systems in which the components (that assemble) are self-propelled.

A. Systems with Externally Propelled Components

In systems with externally propelled components, modules encounter each other at random. The modules are designed to

TABLE I

SELF-ASSEMBLY AND ITS FUNCTION AS EITHER DEMONSTRATED (D:N) OR SYSTEMATICALLY VERIFIED IN REPEATED TRIALS (S:N). 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	Auto-nomy	Constraints	Function
			EXTERNALLY PROPELLED COMPONENTS			
Penrose & Penrose [44]	1-D	✓	✓	✓	-	1-bit replication (D:2)
Hosokawa *et al.* [28]	2-D	-[a]	-	✓	-	formation (S:6)
Breivik [8]	2-D (fluid)	✓	-	-	regulation by environment	growth & replication (D:$\geq$ 16)
White *et al.* [57] (a)	2-D	-	✓	-	-	growth (S:2)
	2-D	✓	✓	-	-	growth & reconfiguration (D:3)
White *et al.* [57] (b)	2-D	✓	✓	-	-	growth & reconfiguration (D:3)
Griffith *et al.* [21], [22]	2-D	✓	✓	✓	-	growth (D:26), 5-bit replication (D:5)
White *et al.* [56] (a)	3-D (fluid)	✓	✓	-	-	growth & reconfiguration (S:2)
White *et al.* [56] (b)	3-D (fluid)	✓	✓	-	-	growth & reconfiguration (D:2)
Bishop *et al.* [5]	2-D	✓	-	✓	-	formation (D:6)
Bhalla & Bentley [4]	2-D	-	-	✓	-	formation (D:10)
			SELF-PROPELLED COMPONENTS			
RSD I [29]	1-D (loop & branches)	✓	✓	-	regulation by environment	0-bit replication (D:2)
CEBOT, Mark II [15]	2-D	✓	✓	-	-	growth (D:2)
CEBOT, Mark III [16]	2-D	✓	✓	-	-	growth (D:2)
CEBOT, Mark IV [17]	2-D	✓	✓	-	-	growth (D:2)
PolyBot, G2 [65]	2-D	✓	✓	-	pre-defined positions	growth (D:2)
PolyBot, G3 [63], [65]	3-D[b]	✓	✓	-	pre-defined positions	growth (D:2)
CONRO [47]	2-D	✓	-	-[c]	limited approaching angle	growth (S:2)
SMC [25], [61], [62]	2-D	-	✓	✓	pre-defined positions, synchronized execution	task-oriented reconfiguration (D:4)[d]
	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 [23], [26], [43]	2-D (flat & rough)	✓	✓	✓	-	grow (S:16), task-oriented growth (D:7, S:3, S:4)
Molecubes [40], [66]	3-D (lattice)	-	✓	-	pre-defined positions	growth & 0-bit replication (D:4)
M-TRAN III [37]	2-D	✓	✓	-	limited approaching angle	growth & reconfiguration (S:2)

[a]The authors discuss a second design in which modules can be in two distinct states.
[b]Experiments were conducted in the horizontal and vertical plane.
[c]During the experimentation, the modules were tethered to a power supply.
[d]A seed object composed of one parent module and three child modules disassembles and re-assembles.

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], [56].

In the systems of Griffith *et al.* [22] and Bishop *et al.* [5], 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 [56], [57].

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.

B. 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 [35]. At the level of modular entities, propulsion requires more elaborate strategies. This is merely due to the high number of DOF that need 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* [38], [64]. Examples are PolyBot [65], CONRO [11], Molecubes [66], and M-TRAN [39]. 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 [14], [27], [42], perception [9], [27], [36], [65], [66], and computational resources [3], [9], [27], [36].

III. Outcome and Analysis of Self-Assembly Experimentation

Table I provides an overview of the experiments that were performed. Details on the experimental setup and results can be obtained from the references listed in the first column of the table. 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 second column). The systems of White *et al.* [56], PolyBot [63], and swarm-bot [23] represent some initial 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 50 or more modules, and typically no more than two separate 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 [23], [28]. Hosokawa *et al.* analyzed the process dynamics with focus on the yield of desired products (with six discrete components per entity). In swarm-bot, 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).

IV. Process Control

The process of self-assembly is governed by the modules' way to encounter each other and by the modules' 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.* [28] and Bhalla & Bentley [4]. In all other systems, a module's motion and/or binding preferences can depend on its state (see third column of Table I). 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 [44]. In the system of Breivik, the state is affected also by the temperature of the environment [8]. In swarm-bot, each module broadcasts its connection state to modules in its vicinity [23].

In 17 out of 22 systems, self-assembly is seeded by a dedicated component (see column 4 of Table I). 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 [43]. Among systems with self-propelled components, only CONRO demonstrated self-assembly without any seed component [47].

Seven out of 22 systems were autonomous in perception, control, action, and power (see column 5 of Table I).[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.* [44] and Breivik [8], or in software, as in

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

all other state-based systems. In Bishop *et al.*'s system [5], 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 [23], [67]. Attempts to port a controller from one physical system to another are still rare and typically require the platforms to share some common properties [25].

In some systems self-assembly was reported to take place under constrained conditions (see column 6 of Table I). Examples are a priori assumptions on the components' initial spatial arrangement and components with knowledge of their own relative starting positions. Clearly, it is more demanding to realize self-assembly in a system of disordered components that lack any knowledge about their relative positions.

TABLE II

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 [27] search & rescue [35] self-construction [50] self-repair devices [2] space robotics [49] under water robotics [55]	social insects [52]
mesoscopic	3-D displays [19] computation [46] drug delivery systems [18] manufacturing [13] microelectronics [20]	origin of life [12] self-replication [21]

V. FUNCTIONALITY

The last column of Table I 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 [26], [54], and (ii) locomotion over terrains unnavigable for individual modules [23], [43].
- **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 [61], [62].
- **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 [29] and Molecubes [66]), pre-assembled seed entities with information in the modules' state (e.g., as in Penrose's [44] and Griffith *et al.*'s [21] systems), or products of the self-assembly process (e.g., as in Breivik's system [8]).
- **self-repair**: replacement of an entities' defective modules with its redundant modules or other modules available in the environment.

VI. CONCLUSIONS

During the last 50 years, a variety of systems were designed displaying self-assembly of discrete components at the macroscopic scale. In this paper, we presented an overview of this research. We identified 22 systems for which self-assembly was demonstrated. We discussed their physical and electrical design characteristics, the outcome and analysis of self-assembly experimentation, the mechanisms that controlled the process of self-assembly, and the functionality that was provided.

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 references to video recordings and additional material, that are available in [24].

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 [58]. Table II gives a broad flavor of potential scientific and technological areas that—according to investigations reported in the current literature—could benefit from the study of macroscopic systems.

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 (and their function) on the other side. In most studies in the literature, 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, and functions. Some promising first steps have already been taken by the development of compilers [30], [31], [41] that take as input a desired pattern or structure and generate a suitable rule set for a system of simple components. However, current compilers are limited in the range of patterns and structures they can process, and are not yet capable of capturing the physical properties of the formed entities. Rothemund [46] 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.

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 require complex computation, actuators, and sensors. 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 [6], [7], [20], [51], [53]. Components at this scale can exhibit a similar range of physical interactions as components at the micro- or even nano-scale. One challenge is the transfer of knowledge gained with the design of macroscopic systems to the design of mesoscopic systems and vice versa.

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