Working Towards Self-assembling Robots at All Scales

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Abstract

From crystals to galaxies, self-assembly is evident throughout nature at all scales. Self-assembly in natural systems is primarily dictated by the morphology of the components within a system and the environmental conditions they are subjected to, as well as their component and environment physical and chemical properties. Several experiments are discussed that demonstrate how to harness these principles of self-assembly to create two-dimensional, physical, geometric mesoscale structures. Primarily, these experiments demonstrate how the relationship between component shape and an assembly protocol can be used to create defined entities of varying form, and could be used as a method for creating more sophisticated netted systems by leveraging the physical attributes of a system. Based on the successful results of these experiments, an evolutionary computation model for applying the principles of self-assembly in nature is also presented, as an approach for working towards the creation of self-assembling robots from the macroscale to the nanoscale.

Keywords: self-assembly, evolutionary computation, nanorobotics, swarm robotics, modular robotics

1 Introduction

Self-assembly (the autonomous construction of a device by itself) is a dream of robotics engineers. A payload of self-assembling components would be easier to transport to hazardous and distant locations compared to complete robots. A device that can self-assemble also has the ability to self-repair or regenerate damaged parts of itself, given replacement components. But, the creation of self-assembling devices is a highly challenging problem.

The concept of self-assembling robots has been a popular theme in science fiction for many years. Only recently have robots been developed that display self-assembly characteristics. These robots are examples of netted systems [1], consisting of sensors and controllers that interact and self-assemble through data communication. These robots demonstrate the synthetic realization of templated self-assembly [2, 3], biological self-assembly [4], and self-reconfiguration [2, 5, 6 , 7, 8], as examples from the disciplines of modular robotics and swarm robotics. However, such disciplines do not provide a generic methodology to creating self-assembling robots at all scales. This is largely due to scalability issues in relation to their respective methods of communication and assembly between modules or robotic-units.

Here, we refine the term self-assembly and suggest that it should be used to describe processes that can be controlled by an appropriate design of pre-existing components that interact in order to create emergent aggregate forms [1]. This view of self-assembly is used to link the principles self-assembly from nature to previous work in robotics and design. Based on this, a general framework is presented that describes the necessary attributes to design a self-assembling system. Experiments and results involving the creation of two-dimensional, physical, geometric mesoscale structures are discussed, to demonstrate how to leverage the self-assembly framework. In addition, an evolutionary computation model [9] is presented as a method to illustrate how harnessing the principles of self-assembly in nature can be used as a design process for working towards self-assembling robots at all scales.

Applying the principles of self-assembly to robotics has tremendous potential. This is especially true at the micro and nano scale, where self-assembly is viewed as the only viable means of fabrication [1].

2 Background

L.S. Penrose and R. Penrose were the first to show a mechanical analogue to natural self-assembly, specifically self-reproduction in the form of templated self-assembly [10]. They created two component shapes, labelled A and B, that connected in either an AB or BA configuration. Multiples of these A and B components were confined to a track in a random ordering, that when shaken, allowed components to move horizontally and interact with one another. By placing either an AB or a BA seed complex on the track, it would cause neighbouring A and B or B and A components to self-assemble into AB and BA complexes respectively.

This example of templated self-assembly has recently been extended to robotics [3]. In this case, triangular-shaped programmed electromechanical components move randomly in two-dimensions on a cushion of air. When components collide, they communicate and latch and unlatch accordingly. Again, by initially placing a seed complex, free components can self-assemble and construct replicas of the seed complex [3].

In these two examples, templates are used to direct the self-assembly process of decentralized components. In contrast, swarm robotics uses swarm intelligence to direct the self-assembly process of decentralized robotic units, in a form of biological self-assembly. Of the robots produced in this discipline, Swarm-bot has shown successful results in mimicking self-assembling formations of social insects (e.g. the formation of living bridges by *Oecophylla longinoda* worker ants) [4]. Swarm-bot is the collective name to the set of cube-shaped mobile robotic units, named s-bots, which are capable of physically linking together. For example, s-bots can self-assemble into aggregate structures to move across terrain, otherwise not possible by an s-bot solely.

The discipline of modular robotics has produced self-reconfigurable robots using both decentralized and centralized control systems [5]. These robots posses the ability to self-reconfigure a pre-exisiting set of modules that are physically connected together, and that move and attach/detach in terms of the degrees of freedom allowed by the components.

Using a hormone-inspired communication method between robotic units, CONRO is an example of a modular robotic system using a decetralized control system [8]. This system facilitates communication betwwen subsets of robotic units, allowing for more roboust self-reconfiguration and locomotion capabilities.

Two of the most successful centralized modular robot implementations to date include PolyBot [6] and MTRAN [5]. PolyBot (a precursor to CONRO) uses cube-shaped modules with one axis of rotation, which are capable of self-reconfiguring into various forms with movement such as in a loop, and in a snake-like and spider-like fashion [6]. MTRAN modules consist of two semi-cylindrical parts connected by a link, with each part being able to rotate 180 degrees about its axis. Each semi-cylindrical part has four permanent magents, on its three surfaces, allowing modules to attach and detach from one another. These modules allow MTRAN to self-reconfigure into forms with one type of crawler and two types of quadruped movement [5].

The use of magnetism as an assembly mechanism to facilitate self-reconfiguration of robotic units has also been leveraged to create modular robotic systems capable of templated self-assembly [2] and self-reproduction [7]. These two examples incorporate self-reconfiguration as intermediate steps, to increase efficiency, in their procedures of self-reproduction and templated self-reproduction.

These robots are all implementations of subsets of self-assembly, in the form of netted systems. In nature, self-assembly is primarily dictated by the design of the components within a system and the environmental conditions they are subjected to, as well as their component and environment physical and chemical properties [11, 12]. The following section describes a general framework for self-assembling system, which covers the above mentioned types of self-assembly currently used in practice (templated self-assembly, biological self-assembly, and self-reconfiguration) and the potential to create self-assembling robots in the future, particularly at the nanoscale.

3 Framework

For the purposes of creating an artificial self-assembling system, the natural principles of self-assembly can be abstracted to four items:

- Components
- Environment
- Assembly Protocol
- Energy

Components are defined by their properties. Such properties include, but are not limited to, shape, scale, material properties, as well as communication methods and interaction methods between components and/or their environment.

The environment in which components are subjected to can provide various functionalities, such as a boundary to which components are confined to. The physical and chemical properties of the environmental will also influence the nature in which components interact with one another, as well the way in which components self-assemble.

An assembly protocol defines the methods in which components can self-assemble (e.g. methods of attraction and repulsion). These methods are highly dependent on the scale of the system, as well as the physical and chemical properties of the components and the environment.

In order for the components to self-assemble, the components need to be mobile in their environment. This requires the components to have energy. This can either be available internally or transferred to components, for example, by the environment.

This self-assembly framework should be considered from the viewpoint of specific self-assembling systems. Physical constraints are normal in such systems, as we can observe in nature. A sand dune will only form in specific circumstances; if the wind force is not sufficient, it will not form. However, by continuing to gain a deeper understanding of self-assembly in nature, it can be leveraged for the purposes of design. This of course can be utilized by robotics, and the creation of simple self-assembling mechanical structures (e.g. pivots, joints, and levers) would be a fundamental next step.

4 Experiments

One possible solution to creating simple mechanical structures is to utilize the relationship between component shape and an assembly protocol. Here, the relationship is investigated in the context of creating two-dimensional, physical, geometric mesoscale self-assembling structures.

Experiments were conducted to investigate whether a set of two-dimensional components (with concave and/or convex polygon shapes) could self-assemble into a desired shape. The assembly process is initiated by placing components on a tray, which is shaken in parallel to the surface of the tray. In this way energy is transferred to the components in the form of vibration, causing the components to move around and interact with one another; and magnetism is used to enable the components to attract and repel one another.

In this context, a component must have two essential properties; the first being the ability to fit together to form the desired shape and the second being the ability to join selectively to corresponding components or not to conflicting components. To achieve the first point, a set of components must include both concave and convex component shapes. By the components' shapes being both concave and convex, components are able to create stronger joints, leading to more stable structures overall, and less likely to break apart when colliding with other components or the sidewalls of the tray, compared to if components' shape were restricted to convex forms only. The second point is achieved by placing a magnet in the interior of a nonmagnetic material. The magnets allow components having opposite polarity to attract and assemble together, whereas components having similar polarity will repel each other, and therefore not assemble together. The nonmagnetic material is used to determine the polygon form of the components. By not allowing the magnets in the components to join directly together, the components have a higher degree of freedom to move around in the given space and interact with one another. Figure 1 shows the principals behind the design of the components.

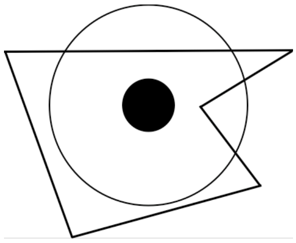


Figure 1: Component design. The solid black circle represents the magnetic disc. The outer circle represents the area of the magnetic field. The irregular pentagon represents the non-magnetic material that defines the shape of the component (the left and bottom of the component are the areas not affected by the force of magnetism).

The components are placed on a tray, which allows a space in which the component shapes can move around and interact with one another. Movement of the components and their interaction is dictated by two-dimensional rigid body dynamics and magnetism. Figure 2 shows the three stable two-dimensional formations of magnetic discs.

Figure 2: The three stable two-dimensional formations of magnetic discs: grid (left); chain (centre); and triangular (right).

To test the validity of this design, five experiments were conducted. Components were constructed out of foam board, magnetic discs, and scotch tape. The tray was constructed out of foam board, pushpins, and

Table 1: Experiments.

Experiment	Number of Component Shapes	Symmetric vs. Non-Symmetric Component Shapes	Magnetic Formations
1. Triangle	4	symmetric	triangular
2. Square	4	non-symmetric	grid
3. Parallelogram	6	3 sets of 2 of symmetric shapes	grid and chain
4. Irregular Octagon	7	1 set of 4 symmetric shapes, and 3 non-symmetric shapes	chain and triangular
5. 16-sided Polygon	10	non-symmetric	grid, chain, and triangular

general purpose adhesive. Each of the five experiments had a different number of components and different desired final forms. Symmetric and non-symmetric component shapes, along with the three stable two-dimensional magnetic disc formations, were also tested to see if they had an effect on the self-assembly process. Table 1 summarizes the design and purposes of each of the five experiments.

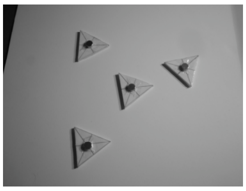
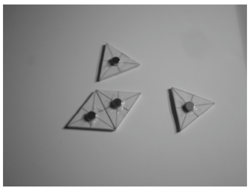
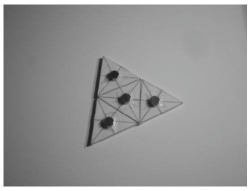
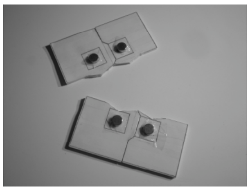
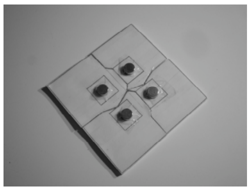
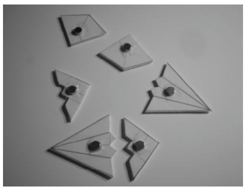
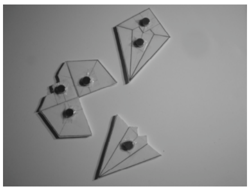
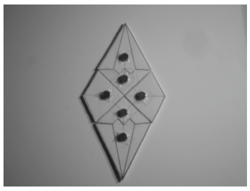
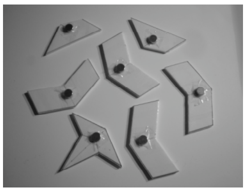
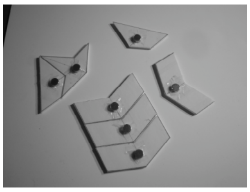
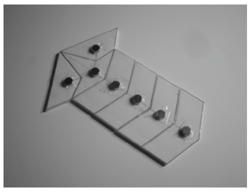
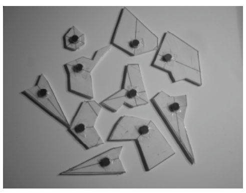
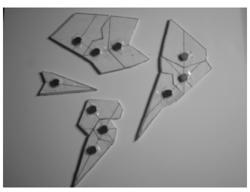
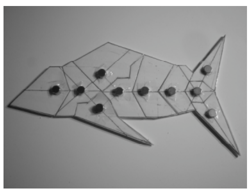
5 Results

Each of the five experiments were successful in having their set of components self-assemble into their corresponding desired final form. Symmetric systems and systems with a lower number of components were able to self-assemble faster in general, in comparison to non-symmetric systems or systems with a large number of components. Table 2 shows the results of the five experiments.

These results demonstrate how the relationship between component shape and an assembly protocol can be used to create self-assembling entities of varying form. Although this combination of shape and an assembly protocol (magnetism) does not apply to all scales, it does however suggest that physical (as well as chemical) properties of a system can be leveraged to aide in creating netted systems.

This relationship of component shape and an assembly protocol allowed for a larger set of feasible self-assembling entities (in the context of the experiment setup and design). In particular, this combination allowed for the exploitation of an effective magnetic force (regions of a component in

Table 2: Experiment results.

	Configuration		
Experiment	Initial	Intermediate	Final
1. Triangle			
2. Square			
3. Parallelogram			
4. Irregular Octagon			
5. 16-sided Polygon			

which the effects of magnetism were subjected to neighbouring components) to create closed self-assembled forms. These forms, in contrast to open forms, do not allow for free components to self-assemble to the entity, when it reaches its target end state. This emergent property is achieved by the way in which component shape is utilized. By allowing a component's shape to be larger than the effective magentic force region, components of opposite magentic polarity are not able to join together, because the magnetic force is not greater than the force of friction between the components and the surface of the tray. Closed self-assembled forms are of particular interest to self-assembling robotics.

Another application of these results is that they demonstrate that physical properties, in this case shape and magnetic attraction/repulsion, can be used as a physical encoding, and as a communication mechanism between components. This concept could also be extended to chemical properties. Physical and chemical properties could be used to replace, simplify, or enhance communication and interaction mechanisms between modules or robotic-units, in self-assembling robots.

Understanding and utilizing the principles of self-assembly in nature, could be used for the realization of nanorobots. At the nanoscale, self-assembly is considered as the only viable means of fabricating entities [1]. At this scale, as well as all others, numerous variables affect the process of self-assembly. Optimization algorithms can be used to generate the specifications of the components and environment to create self-assembling systems [9].

6 Evolutionary Computation Model

With its ability to navigate through complex problem spaces, evolutionary computation has poven to be an extremely useful approach to solving optimization problems. As well, evolutionary computation can be used as a creative tool. This is most notabily seen in its ability to generate novel designs [13]. This duality of evolutionary computation makes it a prime candidate to be incorporated into a process for designing and physically creating self-assembling systems [9].

One embodiment of this process [9] can be described as an eight-step process. These steps include:

1. Define the properties of the desired self-assembling entity.
2. Encapsulate the component design, environment design, and/or construction process (refering to the methodology in which the components and/or environment would physically be created, e.g. using rapid prototyping techniques). This encapsulated information would be encoded into the genotype and phenotype representations of the components and environment.
3. Define the translation process in which the computer generated designs can be used to physically create the components and/or environment (e.g. translating the software representations of the components and/or environment to CAD files).
4. Create software that incorporates a computer model using evolutionary computaion to virtually design and test the candidate components and/or environment, to allow for self-assembly of the components into the desired entity.
5. Execute the software to generate the designs of the components and/or environment.
6. Execute the translation process of the computer generated component/and or enviroenment designs, to a form that can be used for physical fabrication.
7. Build the components and/or environment.
8. Place the components in their environment to allow for the components to self-assemble into the desired entity.

In this evolutionary computation model, the notion of a design space (the set of buildable designs of components and/or environment) is crucial. If this space is ill-defined, it will greatly affect the performance of the software, as well as inhibit the creation of the self-assembling system.

The encapsulation of a design space is a complicated task. However, it is of great importance, especially in using this process [9] for creating physical system, such as self-assembling robots. Using this process [9] to create simple self-assembling entities with features of simple mechanical machines (e.g. pivots, joints, and levers) would be an important next step, with benefits from the macroscale to the nanoscale. Preliminary results from an implementation of this embodiment, which used a genetic algorithm to evolve shapes and a simulator to model their interaction are described in [14]. Work on this area is ongoing by the authors.

7 Conclusions

The principles of self-assembly in nature should be considered when creating self-assembling robots. The general framework (consisting of a set of components, an environment, an assembly protocol, and energy) provides a method for understanding the requirements of a specific self-assembling system.

Experimental results showed that this framework yielded two-dimensional geometric self-assembling mesoscale structures. This was achieved through understanding the relationship between component shape and an assembly protocol. This relationship allowed for the creation of closed self-assembled forms, as well as insight into the use of this relationship to physically encode communication and interaction mechanisms. This could be used to replace, simplify, or enhance communication and interaction mechanisms between modules or robotic-units in self-assembling robots.

As well, an evolutionary computation model was outlined, as a method for working with the numerous variables affecting the process of self-assembly. The process described [9] could be used in working towards self-assembling robots at all scales.

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