Self-organized Segregation Effect on Water Based Self-Assembling Robots

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Abstract

Complex systems involving many interacting components being out of equilibrium often organize into patterns. Understanding the underlying principles that govern such systems might lead to a deeper insight into living systems and the development of new applications in robotics. In this contribution, we investigate water-based self-assembling modules, exhibiting a segregation effect under some particular conditions. The system consists of vibrating (active) and non vibrating (passive) circular modules floating on the surface of the water. The segregation happens as a result of a depletion-like force, which is of purely entropic nature and is based on the characteristics of the modules (active or passive). We focus especially on the dynamics of the process with respect to the energy and the entropy. Some applications of the designed system are also discussed.

INTRODUCTION

Self-organization is one way by which nature builds artefacts at various scales. Nature offers diverse examples: the formation of molecular crystals [9], the folding of polypeptide chains into proteins [17], the folding of protein into their functional form [20], the cell's spontaneous organization into tissues [18], bacteria into colonies [10] [6], the formation of swarms (flock of bird or school of fish [23]) at a higher level, are commonly achieved in a distributed manner, where there is no central control system.

In the industry, as the aimed size of products decreases, people have started to recognize the advantages of self-organization in general and self-assembly in particular – which is typically approached in a bottom-up fashion. The potential capability as an alternative to replace traditional manipulating methods by self-assembly has been brought to attention. Standard manipulators have shown some limitations in the manipulation of nano-scaled components and there is a need for alternative methods with the miniaturization in the nanotechnology industry. *Nanogen Inc* employs electric field-mediated self-assembly to bring together DNA nanocomponents for electronic and diagnostic devices [13]. *Alien technology Corporation* uses self-assembly techniques like shape recognition or fluid transport to fabricate micro-scaled RFID tags [8][28].

One collective behavior that can emerge as result of local interaction is segregation, that is a spatial sorting method, where a group of objects occupies a continuous area of the environment which is not occupied by members of any other group. Segregation plays a key role in the food and drug processing industry. In particular, when shaking foods made of particles or granular material of different sizes, segregation effects occurs and the underlying mechanism is known as the *Brazil nut effect* or the *muesli effect* [24]. This spontaneous ordering goes against one's intuition that objects get mixed when merged in random directions and was described by Barker and Grimson in this way: "During the periods when shaking loosens the packing, individual small particles can move into voids beneath large particles and so prevent them from returning to their previous positions. It is far less probable that several small particles will move together so as to create a void that can be occupied by a single large particle. The net effect is that the smaller particles occupy the lower positions during the active part of the shaking process and then become trapped there when the grains fix into a new arrangement." [3]. A similar phenomenon takes place in the industrial production of drugs, thereby yielding considerable risks for patients (who are assumed to consume homogeneous mixings).

Many self-assembly and self-organizing systems have been suggested using different approaches, several of them inspired by biology. The best known example in this domain is probably the Reynolds flocks of birds [23], where different agents generate a flocking behavior by means of simple rules: collision avoidance, speed and heading matching and maintaining a close distance to the neighbor flock mates. The collision avoidance enables the agents to avoid colliding with each other; the second rule enables the agents to match their speed with their neighbors speed, whereas the third rule enables them to maintain a close distance to the neighboring birds. Reynolds simulations of the flock of bird show that these local interactions produce a global behavior similar to the flocks of birds we observe in the nature. Reynolds work doesn't only provide a tool to understand how the real flocks of birds achieve their global behavior but also help to design machines with formation control capabilities. Whitesides *et al.* assessed dynamic self-assembly would be one of the key challenges in building self-assembly systems [26] and in understanding life. Their suggestion relies on the fact that the most living systems are dynamic and understanding dynamic self-assembly would probably also leads to understanding life. Pfeifer *et al.* proposed a new approached in the design of robotics systems in general and living systems in particular. They suggested a synthetic approach taking morphological aspects into account [22].

There are three basic issues with this picture: (1) although little is known about the underlying assembly process, the fact that many living systems adopt similar mechanisms hints at common design principles suggesting that simplified models (such as the one presented in this paper) might be helpful in understanding the process; (2) even for a small cells, there are too many possible intermediates to allow a complete description of the assembly process with three independent stages [10]; and (3) a generalized scheme to avoid a substantial degree of incorrect assembly has to exist.

To date a few self-reconfigurable modular robots relying on stochastic self-assembly have been built [4][7]. White *et al.* studied two systems in which the modules binding preferences are coded in a program executed by an on-board microcontroller, and thus can easily reconfigure the structure [25]. The modules are initially unpowered and passive, but once they bind to a seed module connected to a power supply, they become active. Griffith *et al.* studied a system of template-replicating modules [12]. They used modules of the same type, which are programmable and can store distinct states. The system demonstrated the self-replication of a five modules polymer. Each module executed a finite-state machine. Klavins *et al.* examined the problems of designing a grammar that causes modules to assemble into desired products, of predicting the time complexity of such processes, and of predicting (and optimizing) the yield of such processes [15]. Emergent self-propulsion mechanisms were investigated by Ishiguro *et al.* [14]. In Ant-inspired robotics, the interest in self-organization has been driven by the observations of the same phenomena in ant colonies, in particular the brood sorting by *Temnothorax* [11]. *Wilson et al.* [27] created an algorithm to realize two colors annular sorting which used differential pull-back distances for different object types. By discriminating between three puck types, the robots could drop the first type of object on colliding with another puck, drop the second object type after pulling back a short distance and drop the third puck type after pulling back a further distance.

The Tribolon platform developed in our group is an example of a system using the morphology, which means the form and the shape of the involved components to get self-propelled robots to self-assemble [19]. Previouly, we carried out several experiments with circular sector shaped modules that can assemble to a single module. To overcome the restraint that the system has some difficulties to possess global information, the designer is supposed to consider the characteristics of the system and design new in/out scheme and apply an adequate controlling method to the robots. If the units move around by other means (e.g., by exploiting surface tension or by taking advantage of Brownian motion), the system is stochastically self-reconfigurable implying variable reconfiguration times and uncertainties in the knowledge of the units location (the location is known exactly only when the unit docks to the main structure). The advantages of this form of reconfiguration are at least two-folds: it can be extended to small scales, and it alleviates local power requirements.

In this paper, we show how segregation effects can be achieved on our platform. An important part of our modelling is the introduction of passive and active modules. We will see how these two types of particles successfully segregate and describe the dynamics of the segregation behaviour by discussing the center of mass of each cluster and the entropy of the system.

THE EXPERIMENTAL SETUP

The Model

The term self-assembly implies that the elements or parts involved assemble in a spontaneous manner without external intervention or control. Taking this into account, we chose to produce a set of modules with the same shape that swarm on water.

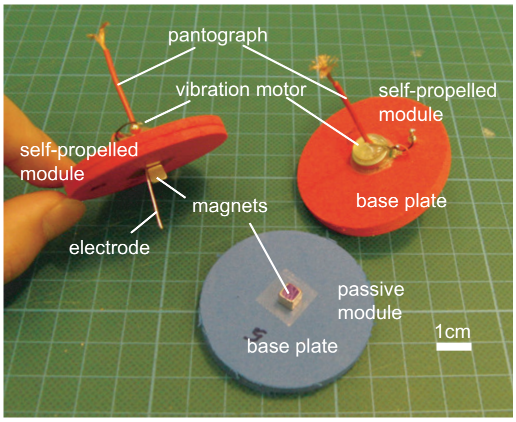

Figure 1: (a) Self-propelled and passive modules. Each module weighs $2.8\,g$ and has a footprint of $12.25\,cm^2$.

To conduct the experiments, we used the Tribolon platform [19] consisting of centimeter-sized modules floating on the water surface. All the modules are equipped with a permanent magnet attached at the bottom and aligned in a way so that they repel each other (north is always pointing up). Some of the modules are, in addition to the permanent magnet, also equipped with a vibration motor. In this paper,

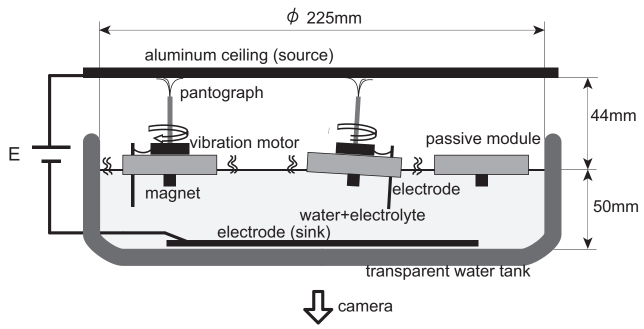

Figure 2: Illustration of the experimental environment with three modules.

we will denote a module provided with a vibration motor as vibrating or active module and a module only provided with a permanent magnet as passive module.

The vibrating modules are equipped with a flat coreless vibration motor (T.P.C DC MOTOR FM34F, $12000 \sim 14000\, rpm\, (2.5 - 3.5\, Volts)$) on the top of the base plate to allow self-propulsion, and all the modules with a single cubic permanent magnet (flux density $1.3\,T$, $5 \times 5 \times 5\, mm^3$, we decided that a single module should contain only one magnet) at the bottom for attractive/repulsive interactions (Fig. 2). This allowed the modules to jiggle and move around in their environment. A pantographic mechanism was used to supply the vibration motor with energy. When an electrical potential was applied to the ceiling plate (see Fig. 2), current flowed through the pantograph to the vibration motor was applied to the ceiling plate, current returning to ground via electrodes immersed in the conductive water.

Due to this setup, all modules receive the same constant power and they are be lightweight ($2.8\, g$ each), which would not be the case if batteries were used.

The Interaction Mechanism

Long-range interactions between two modules depend only on the force between the magnets on the tiles. We consider the magnets as dipoles with a magnetic moment $\boldsymbol{m}$.

The magnetic potential $\phi_j(\boldsymbol{r})$ at a position $\boldsymbol{r}$ due to the magnetic moment $\boldsymbol{m}_j$ is given by

$$\phi_j(\boldsymbol{r}) = \frac{\mu_0}{4\pi} \frac{\boldsymbol{m}_j \cdot \hat{\boldsymbol{r}}}{r^2} \tag{1}$$

where $\mu_0 = 4\pi \times 10^{-7} Tm/A$ is the permeability of free space, and $\hat{\boldsymbol{r}} \equiv \boldsymbol{r}/|\boldsymbol{r}|$ assuming that $|\boldsymbol{r}| = r$ is much larger than the size of the magnet. The magnetic flux of the dipole is then given by

$$\boldsymbol{B}_j = -\nabla \phi_j \tag{2}$$

and the magnetic potential energy U_{ij} acquired by a second dipole $\boldsymbol{m}_i$ placed in the field of $\boldsymbol{m}_j$ is given by

$$U_{ij} = -\boldsymbol{m}_i \cdot \boldsymbol{B}_j. \tag{3}$$

Then, the force between the two dipoles is found by differentiating (3) with respect to $\boldsymbol{r}$.

$$\boldsymbol{F}_{ij} = (\boldsymbol{m}_i \cdot \nabla)\boldsymbol{B}_j \tag{4}$$

$$\boldsymbol{\tau}_{ij} = \boldsymbol{m}_i \times \boldsymbol{B}_j \tag{5}$$

We can determine the total potential energy of the system as

$$U_{total} = \frac{1}{2} \sum_{i,j\; i \neq j} U_{ij}. \tag{6}$$

Finally, we normalize the energy as $U'_{total} \equiv U_{total}/(\frac{\mu_0}{4\pi} m^2)$. The long range interaction described above is identical for each type of modules, since identical magnets were used. However, the short range interaction, i.e. the final alignment, is dominated by the non-linear dynamics and will be explain later in this paper.

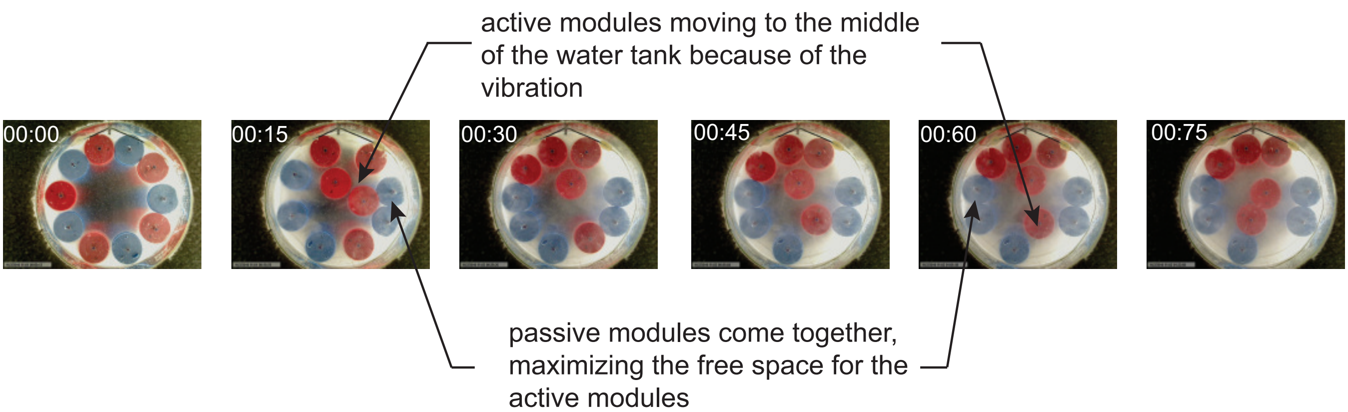

Figure 3: The experimental results in time sequence. The frames are captured every 15 seconds

THE EXPERIMENTAL RESULTS

Global Observations

In the following part, we investigate how designed system achieves a global segregation effect. We setup experiments with ten modules, where five red colored modules are "passive" and the remaining blue colored modules are "active", meaning the vibration motors are implemented. For the purpose of this investigation, fifteen experiments were conducted. In Fig. 3, we show a representative result in time sequence of the obtained segregation behavior. The starting conditions were set as depicted in Fig. 3 (00:00), in which all the modules are placed in a circular form alternately, such that the passive and the vibrating modules have equal chances in the segregation process. This configuration also allows us to make a statistical analysis with very similar starting conditions. The duration time for the experiment was set to 90 seconds. In order to perform the analysis, fifteen experiments were conducted and the trajectories (positions) of all the modules were tracked using the open source tracking software "Tracker Video Analysis and Modeling Tool" [5].

Our observation is that the red active modules tend to assemble together and go apart from the blue passive modules, such that two different modules clusters can be spatially distinguished; the first cluster contains only the active modules and the second cluster the passive modules (see Fig. 3 (00:75)).

In the following sections, we analyze and prove the segregation behavior using statistical methods, by calculating the potential energy, the entropy and the centroids distance of the two clusters. The reader should notice that the calculated values for the entropy, the potential energy and the centroids are mean values over the fifteen experimental trials. The error bars represent the standard deviation of uncertainty within the fifteen experimental trials.

Potential Energy Transition

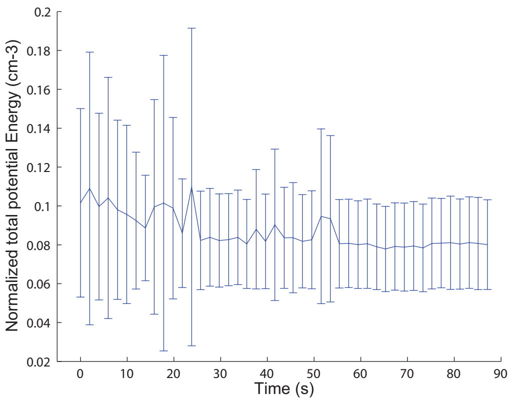

Figure 4: Total Energy of the system.

The potential energy of the system is defined as in Eq. 6. We calculated the total potential energy of the system according to that equation and Fig. 3 presents the obtained result as function of the time. As displayed in Fig. 3, the system tries to maintain itself at a meta-stable configuration, while the segregation is happening.

If we had the modules free floating on the water surface without any vibration, then the system would tend to minimize its total energy, this means that the distance between the modules would be maximized. It has to be mentioned that the system is a non-equilibrium system.

The Centroid Distance

In this section, we show the cluster formation using the centroid of the system.

The centroid $(X, Y) = (\frac{1}{N}\sum_{i=1}^{N}(x_i), \frac{1}{N}\sum_{i=1}^{N}(y_i))$ of a group of modules is the center of mass of the modules, where N is the number of modules in the modules group, x_i and y_i respectively the positions of the i-th component of the considered group). We calculated the time evolution of the difference between the two modules groups (the passive modules on one side and the active modules on the second side).

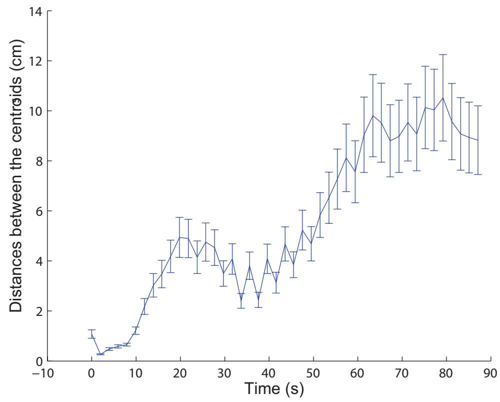

Figure 5: Time evolution of the distance to between the center of mass of the two clusters.

As depicted in Fig. 5, there is an increase in the distance between the centroids of the passive and the vibrating modules. This corresponds to the formation of two clusters of modules with a final mean distance between the two clusters of approximately 10 centimeters.

Entropy

The definition of entropy differs in scientific fields, depending on to what one applies. Thermodynamics entropy (to heat), statistical mechanics entropy (to object), and information entropy (to event) are probably the three best known entropies in science. In self-assembly, systems that cannot presume some specific physical amounts, such as quantity of heat, employ information entropy for the measurement of their "randomness".

Balch proposed a novel definition of entropy (position order) that can be applied for the measurement of multi-components distributions (or quantitative metric of diversity) [2]. He uses H from Shannon's theory

$$H(h) = -\sum_{i=1}^{N} p_i(h) \log_2(p_i(h)) \tag{7}$$

where p_i is the number of modules in the $i-th$ cluster ($i \in N$) divided by the total number of modules. A component belongs to a cluster if the distance is within the length of h ($||\vec{r_i} - \vec{r_j}|| < h$; $\vec{r_i}$ is the position of the i-th component). He then integrates $H(h)$ over all possible h, and defines it as entropy, namely:

$$S = \int_0^\infty H(h)dh. \tag{8}$$

The definition describes the randomness of modules well. Note that in this definition, the entropy may decreases over time. In physics, an entropic force acting in a system is a macroscopic force whose properties are primarily determined not by the character of a particular underlying microscopic force (such as electromagnetism), but by the whole system's statistical tendency to increase its entropy. We examined the entropy of the system as derived as in Eq. 8. Fig. 6 shows the time evolution of the entropy of the system.

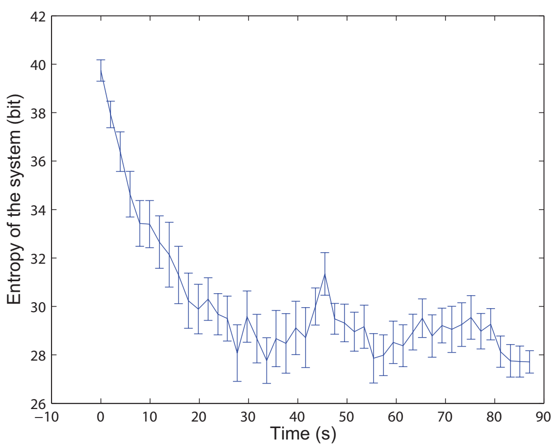

Figure 6: The Transition of Entropy.

As we can observe, the entropy of the system is decreasing within the time, which means that the system tends to converge to a more ordered configuration, which is a property of cluster formation. This shows, that a disordered system has evolved into an ordered system decreasing its entropy.

DISCUSSIONS

Depletion Effect

In this section, we will explain that the passive modules segregate and come together in order to maximize the space available for the active modules. The process, that explains

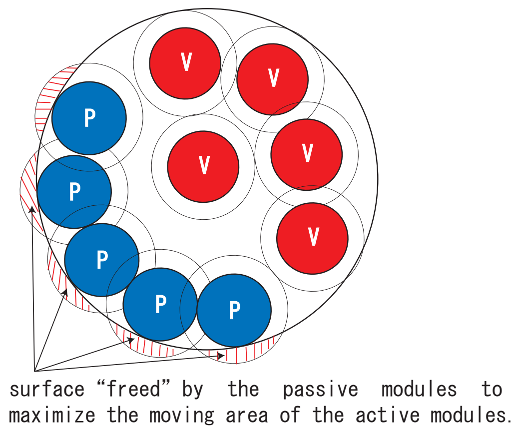

Figure 7: Illustration of the excluded area of the passive modules.

the segregation is depicted in Fig. 7; a module cannot lie in the area around another module due to the magnetic repulsive force. When the passive modules are closed to the wall, the excluded area for the passive modules and the wall overlap (shaded region) and this reduces the total excluded area. This extra area is available for the vibrating modules. As shown here, the overlap is larger when the passive modules are placed next to the curved portion of the wall compared to it being in the middle of the water tank. In the conducted experiments, the vibration acts as an effective short range repelling potential, which results in the observed separation of the passive modules and in consequence an effective attraction between the passive modules. Depletion effects also called exclusion effects are observed at all length scales; especially at the molecular scale, it can be described from a statistical mechanics point of view as a minimization of free energy.

The segregation process is due to the physical non-linear dynamic interaction between all the modules and is illustrated in Fig. 8. In the first step (Fig. 8 a), the vibrating modules tend to go to the middle of the water tank, due to the vibration. In a further step, the vibrating modules maximize their free space by pushing the passive modules to one side of the water tank (Fig. 8 b). This free-space reaches its maximum when all the passive modules are close together and there are no blank spaces between them. The passive modules move towards the wall (as illustrated in Fig. 7). In that way, the free area available to the vibrating modules is larger if a large module is placed next to the curved surface of the wall, than if it is in the middle of the water tank.

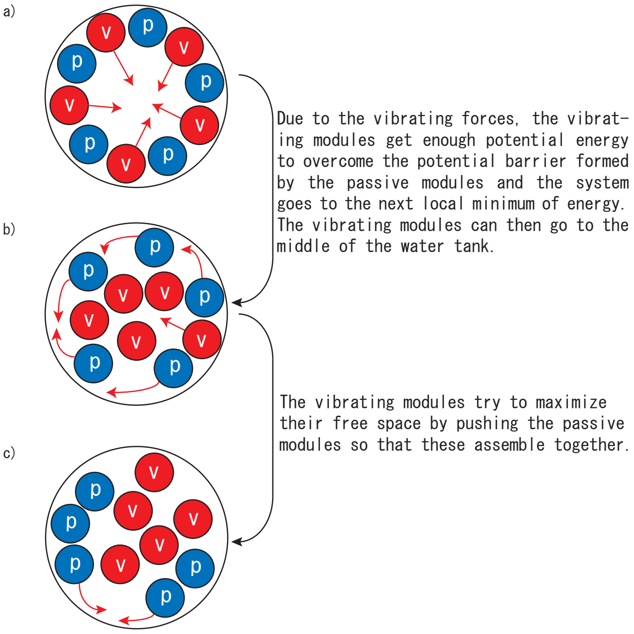

Figure 8: Explanation of the transitions in the experiments

A similar segregation effect is observed in granular mixtures and is known in physics as depletion effect. The segregation criteria can be the size, the shape, the mass or some frictional coefficients and can be caused by several mechanisms, including vibration, percolation, convection and tumbling [16] [21]. The force created by the vibrating modules, which pushes the passive modules together and increases the space available for the vibrating modules, is called depletion force. This force, which is purely entropic in origin has been predicted by Asakura and Oosawa [1] and confirmed since then by several experiments.

Previous experiments and simulations were conducted using passive modules mostly of different sizes and have shown, that a similar segregation can be produced by shaking mixtures of different sizes vertically. This underlying effect is called the Brazil nut effect and big particles, seem to move to the top, while smaller particles move to the bottom. The particularity of our experiments is that it is conducted at the centimeter size, so that we can observe and analyze the phenomena directly using relatively simple techniques (tracking for example) compared to the experiments conducted at the molecular scale. Furthermore, our experiments was conducted in two dimension utilizing also vibrating modules; there is no microcontroller, no sensing, we only exploit the dynamic interaction between the modules to achieve the segregation. This way of proceeding is unusual in distributed system's robotics, where one mostly use distributed algorithms and local rules to reach global patterns.

The advandtage of distributed systems and the potential applications

One can think of many practical applications for a self-segregating system. In a system with a very large amount of microscopic units it would be virtually impossible to locate and remove specific, e.g. damaged, units and remove them manually. If we can introduce a module into this system that can specifically interact with these broken units and separate them from the other modules by pushing them to the edge they exhibit a self-repairing or self-healing function. These also explain the importance of the presence of active modules in this experiment and in dynamic self-assembly in general, since they can be controlled and exploited to facilitate a self-healing process.

One potential application would be to spatially segregate different modules that would normally interfere with each others function of generating a product. These products in turn are not affected by the segregation effect and can freely move and interact with each other again. This has the effect of compartmentalizing individual processes to make them more efficient without introducing a physical barrier that then would also hinder the products movement.

Further the segregation effect might be used by the industry to avoid the Brazil nut effect, by better understanding the mechanisms taking place. By forcing a module out of its position it might occupy due to its size, a more heterogeneous distribution of modules can be achieved.

CONCLUSIONS AND FUTURE WORK

We proposed a stochastic self-assembly system in which a segregation effect emerges as a result of local non-linear interactions between the modules of the system. The system involves passive and active vibrating modules, whose movements are random. Using fifteen experimental trials on a real system, we have shown the expected segregation behavior by applying statistical methods. We believe that understanding dynamic self-assembly will play a key role in the development of small-scaled modular robots and will offer new opportunities to deepen both the realization and the theoretical understanding of self-assembly systems. Furthermore, some of the principles discovered especially concerning the dependence of self-organization on the dynamic interaction between the modules might lead to a better understanding of similar processes found in natural systems and of life in general. When we analyze the behavior of our system, we must be aware that not only the dynamics of the modules contributes to the emergent global pattern that we observed, but also the environment itself (The reader should note that in a different environment, e.g. different border shape or size of the arena, the global pattern described above may be different, which also open perspectives for controlling segregation processes).

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