Self-organized Segregation Effect on Self-Assembling Robots

Aubery Marchel Tientcheu Ngouabeu [1,2], Shuhei Miyashita [2], Rudolf M. Füchslin [2,3],
Kohei Nakajima[2], Maurice Göldi [2], and Rolf Pfeifer [2]
[1] Technical University Munich
[2] Artificial Intelligence Laboratory, University of Zurich
[3] European Centre For Living Technology, Venice, Italy
aubery.tientcheu@mytum.de

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.

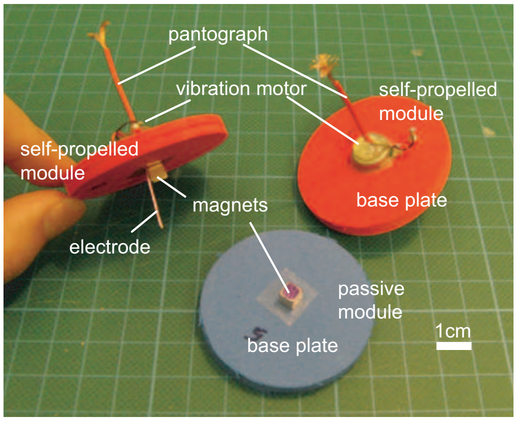


Figure 1: (a) Self-propelled and passive modules. Each module weighs $2.8\,g$ and has a footprint of $12.25\,cm^2$.

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,

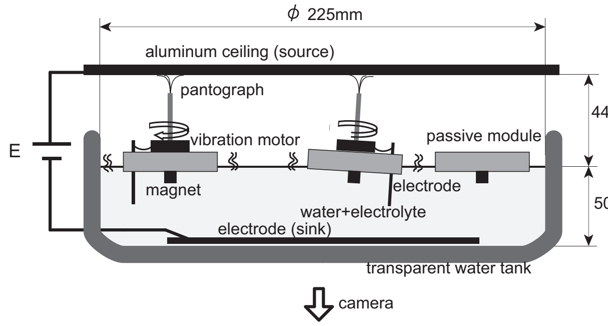


Figure 2: Illustration of the experimental environment with three modules.

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 $1.3\,T$, $5\times5\times5\,mm^3$, 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 $\mu_0 = 4\pi\times10^{-7}Tm/A$ 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

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

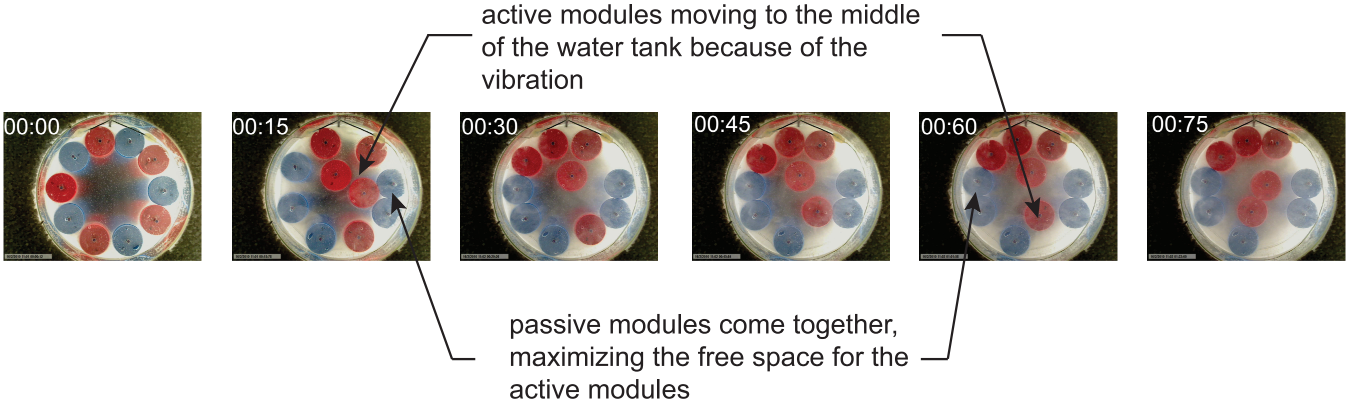
Then, the force between the two dipoles is found by differentiating (3) with respect to $\boldsymbol{r}$.

$$\begin{aligned} \boldsymbol{F}_{ij} &= (\boldsymbol{m_i}\cdot\nabla)\boldsymbol{B_j} \qquad (4)\\ \boldsymbol{\tau}_{ij} &= \boldsymbol{m}_i\times\boldsymbol{B}_j \qquad (5) \end{aligned}$$

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.



active modules moving to the middle of the water tank because of the vibration

passive modules come together, maximizing the free space for the active modules

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

THE EXPERIMENTAL RESULTS

The initial condition

In the following part, we investigate how designed system achieves a global segregation effect. Our experimental setup consists of ten modules, where five red colored modules are ”passive” and the remaining blue colored modules are ”active”, meaning the vibration motors are implemented. We conducted 15 trials for the statistical analysis (see section). In Fig. 3, we show a representative result in time sequence of the obtained segregation behavior. The initial starting condition was set as depicted in Fig. 3 (00:00), in which all the modules were symmetrically aligned 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 similar starting conditions. The duration time for the experiment was set to 90 seconds.

Global Observations

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 investigate 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

The magnetic potential energy of the system is defined in Eq. 6. We calculate the total magnetic potential energy of the system and show the obtained result in Fig. 4 presents the obtained result as function of the time.

Due to the characteristics of the system, non-equilibrium system, the value keeps changing. Suppose we have all passive modules, the system is supposed to reach to the state where modules are equally distributed and fixed.

The Centroid Distance

In this section, we investigate the cluster formation by computing the centroid of the system of the two clusters.

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 (or cluster) 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 are the positions of the i-th component of the considered group, respectively. 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 and depicted in Fig. 5.

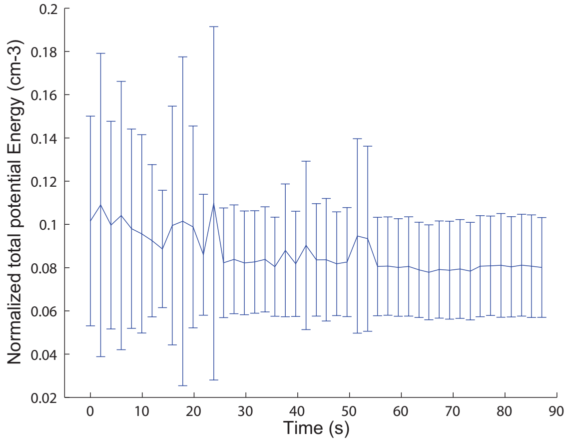


Figure 4: Total Energy of the system.

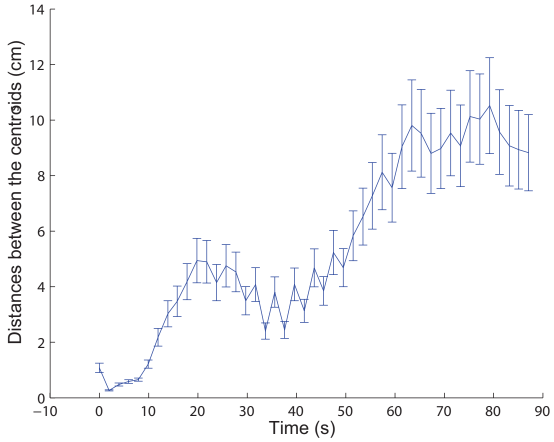


Figure 5: Time evolution of the distance to between the center of mass of the two clusters (N = 15).

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. Given that the diameter of the arena (or tank as you wish) is 22.5 centimers, this corresponds to the 50% of the whole area.

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.

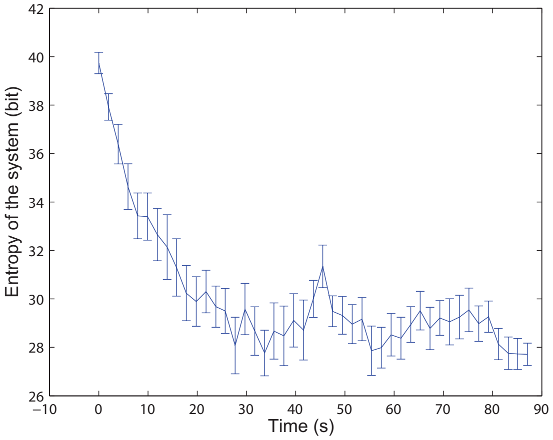


Figure 6: The Transition of Entropy.

As we can observe, the entropy of the system is decreasing as time progresses, which represents the convergence of the system to more ordered configurations. This corresponds to the cluster formation described of the previous section.

DISCUSSIONS

Depletion Effect

In this section, we speculate the main cause of the segregation effect. Fig. 7 illustrates the exclusive regions of modules, where different module have difficulty in lying in the area around another module due mainly to the magnetic repulsive forces. When the passive modules are closed to the wall, the excluded area for the passive modules and the wall overlap (shaded region) and this causes the reduction of the total excluded area. Now the extra area is left for the vibrating modules. As shown here, the overlap is larger when the passive modules are placed next to the curved portion

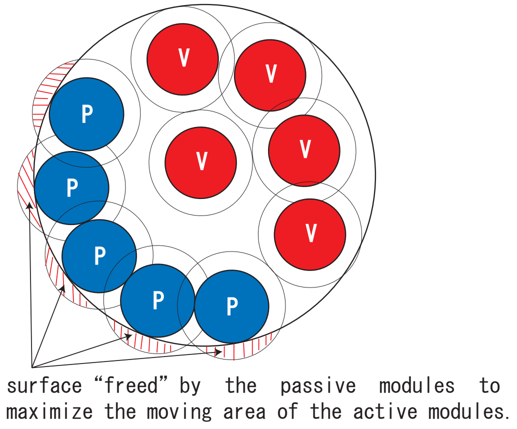


Figure 7: Illustration of the excluded area of the passive modules.

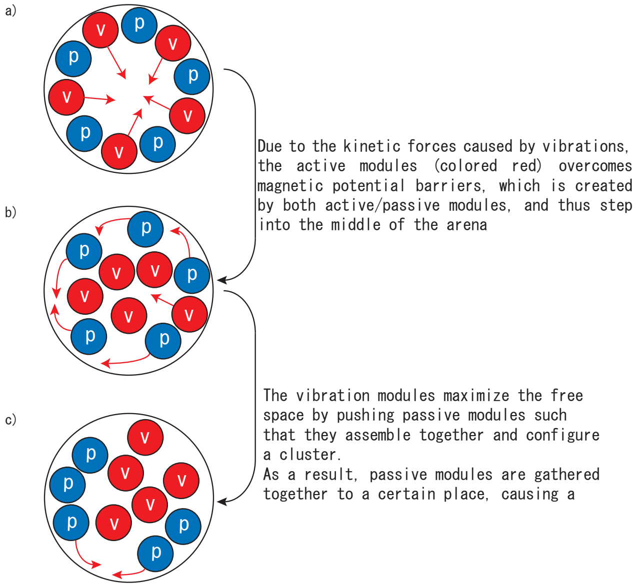


Figure 8: Explanation of the transitions in the experiments

of the wall compared to it being in the middle of the water tank. In the experiments, the vibration motion 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. In nature, depletion effects, which is also called exclusion effect 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 careful observation of the segregation process is described in Fig. 8. At the initial stage (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). The free-space reaches its maximum when all the passive modules are close together and there is no blank space 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.

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. Other work on both 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 ([24]). 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.

Properties of the system

The particularity of our experiments is that it is conducted at the centimeter size, , and not to mention, which helps to observe and investigate the phenomena directly using simple observation tools (i.e. visual tracking for example) compared to the experiments at smaller scales. Furthermore, our experiments were 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

Realizing controlled global segregation behavior of distributed modules offers various applications; here we highlight self-healing capabilities. A system containing a large amount of locally interacting (and cooperating) microcomponents offers considerable problems with respect to maintenance (removing of damaged components as well as recharging). If proper functioning is correlated with segregation behavior, non-functional modules may tend autonomously to the edge of the container where they can be replaced or recharged. Conceptually, this means that at least parts of the control of the maintenance process are embodied in the system. Future production processes may rely on swarms of agents, probably of different morphology and function. Tunable segregation mechanisms offer a potential for inducing a variety of different patterns of the agents under consideration, yielding an additional option for programming swarm based production processes.

Finally, studies of the type presented here may shed light on, in an industrial context, highly relevant class of segregation processes in mixtures of objects of different morphology. Examples are e.g. the Brazil nut effect, but also various types of sieving processes (in which the basically passive granules take up energy from a shaking table in a way that depends on their respective morphology).

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, that randomly move on water in a purely distributed way. By analyzing fifteen experimental trials with statistical methods on a real setup, we have shown the expected segregation behavior, in which passive and active modules induced formed groups, hence causing a segregation behavior. 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.

ACKNOWLEDGMENTS

This research is partially supported by the Swiss National Science Foundation project #200020-118117/1.

References

Asakura, O. (1954). On interaction between two bodies immersed in a solution of macromolecules. *The Journal Of Chemical Physics*, 22:1255.

Balch, T. (2000). Hierarchic social entropy: An information theoretic measure of robot group diversity. *Autonomous Robots*, 8:209–237.

Barker, G. and Grimson, M. (1990). The physics of muesli. *New Scientist*, 126:37–40.

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

Brown, D. (2009). Tracker video analysis and modeling tool. http://www.cabrillo.edu/ dbrown/tracker/.

Budrene EO, B. H. (1995). Dynamics of formation of symmetrical patterns by chemotactic. *Nature*, 376(6535):49–53.

Castano, A., Behar, A., and Will, P. M. (2002). The conro modules for reconfigurable robots. *IEEE/ASME Trans. on Mechatronics*, 7(4):403–409.

Corporation, A. T. (1994). Alien technology website. http://www.alientechnology.com/products.

Desiraju, G. (1989). *Crystal Engineering: The Design of Organic Solids*. Elsevier.

Elena O. Budrene, H. C. B. (1991). Complex patterns formed by motile cells of escherichia coli. *Nature*, 349:630 – 633.

Franks, Nigel R., S.-F. A. B. S. S. R. M. C. (2004). Brood sorting by ants: Two phases and differential diffusion. *Elsevier B.V.*, 68:1095–1106.

Griffith, S., Goldwater, D., and Jacobson, J. (2005). Robotics: Self-replication from random parts. *Nature*, 437:636.

Heller Michael J.; Cable, Jeffrey M.; Esener, S. C. (2003). Methods for the electronic assembly and fabrication of devices. *US Patent 6652808*.

Ishiguro, A., Shimizu, M., and Kawakatsu, T. (2006). A modular robot that exhibits amoebic locomotion. *Robotics and Autonomous Systems*, 54:641–650.

Klavins, E. (2007). Programmable self-assembly. *IEEE Control System Magazine*, 27:43–56.

Kudrolli, A. (2004). Size separation in vibrated granular matter. *Reports on Progress in Physics*, 67(3):209.

Maginn, S. J. (1991). Crystal engineering: the design of organic solids by g. r. desiraju. *Applied crystallography online*, 24:265–265.

Markwald, K. J. A. N. V. M. R. and Forgacs, G. (2004). Engineering biological structures of prescribed shape using self-assembling multicellular systems. *Proc. Natl. Acad. Sci. USA*, 101:2864–2869.

Miyashita, S., Kessler, M., and Lungarella, M. (2008). How morphology affects self-assembly in a stochastic modular robot. In *IEEE International Conference on Robotics and Automation*.

Neidle, S. (1999). *Oxford Handbook of Nucleic Acid Structure*. Oxford University Press.

Ottino, J. M. and Khakhar, D. V. (2000). Mixing and segregation of granular materials. *Annual Review of Fluid Mechanics*, 32:55–91.

Pfeifer, R., Lungarella, M., and Iida, F. (2007). Self-organization, embodiment, and biologically inspired robotics. *Science*, 318:1088–1093.

Reynolds, C. W. (1987). Flocks, herds, and schools: A distributed behavioral model. *Computer Graphics*, 21:25–34.

Rosato, A., Strandburg, K. J., Prinz, F., and Swendsen, R. H. (1987). Why the brazil nuts are on top: Size segregation of particulate matter by shaking. *Phys. Rev. Lett.*, 58(10):1038–1040.

White, P., Kopanski, K., and Lipson, H. (2004). Stochastic self-reconfigurable cellular robotics. In *Proc. Int. Conf. on Robotics and Automation*, volume 3, pages 2888–2893.

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

Wilson M., Melhuish C., S.-F. A. S. S. (2002). Multi-object segregation: ant-like brood sorting using minimalism robots. *Proc. Seventh International Conf. on the Simulation of Adaptive Behaviour, Edinburgh, UK*, page 369370.

Yeh, H. and Smith, J. (1994). Fluidic self-assembly for the integration of gaas light-emitting diodes on si substrates. *Photonics Technology Letters, IEEE*, 6(6):706 –708.