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Crystallization of robotic swarms in a parabolic potential

M.K. Buzakov [1], V.A. Smirnov [1], D.V. Sennikova [1], A.A. Molodtsova [1] ✉,
A.D. Rozenblit [1], V.A. Porvatov [2], O.I. Burmistrov [1], E.M. Puhtina [1],
A.A. Dmitriev [1], N.A. Olekhno [1]

[1] ITMO University, St. Petersburg, Russia;
[2] University of Amsterdam, Amsterdam, Netherlands
✉ a.molodtsova@metalab.ifmo.ru

Abstract. Large ensembles of particles converting their internal energy resources into mechanical motion form a class of systems denoted as active matter. Such systems demonstrate a wide range of interesting phenomena, including self-organization and phase transitions emerging in biological and artificial active matter. One of the popular platforms for experimental realization of such systems are swarms of simple moving robots. In the present work, we consider a swarm of self-propelled robots with a stadium-like shape placed in a parabolic potential and address the dynamics of crystallization in this non-equilibrium system. To quantify the formation of hexagonal crystals, we evaluate the average cluster size and six-fold parameter characterizing the hexatic ordering directly from the experimental data.

Keywords: crystallization, self-organization, active matter, swarm robotics, self-propelled particles

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Исследование кристаллизации скопления роботов в параболическом потенциале

М.К. Бузаков [1], В.А. Смирнов [1], Д.В. Сенникова [1], А.А. Молодцова [1] ✉
А.Д. Розенблит [1], В.А. Порватов [2], О.И. Бурмистров [1], Е.М. Пухтина [1],
А.А. Дмитриев [1], Н.А. Олехно [1]

[1] Университет ИТМО, Санкт-Петербург, Россия;
[2] Амстердамский университет, Амстердам, Нидерланды
✉ a.molodtsova@metalab.ifmo.ru

Аннотация. Скопления из большого числа частиц, способных преобразовывать свою внутреннюю энергию в механическое движение, относятся к отдельному классу систем, называемых активной материей. Для таких систем характерно большое разнообразие коллективных явлений, включая самоорганизацию и фазовые переходы. Одной из

распространенных платформ для экспериментальной реализации активной материи являются скопления движущихся роботов. В настоящей работе мы рассматриваем скопление поступательно движущихся роботов со стадионной формой, помещенных в параболический потенциал, и изучаем динамику кристаллизации в такой неравновесной системе. Чтобы количественно оценить процесс формирования треугольной кристаллической решетки из роботов, мы извлекаем из экспериментальных данных средний размер кластеров и параметр порядка, характеризующий гексагональную плотную упаковку.

Ключевые слова: кристаллизация, самоорганизация, активная материя, групповая робототехника, самодвижущиеся частицы

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Introduction

The physics of active matter considers phase transformations, self-organization, and dynamics of systems whose structural elements can convert internal or ambient energy to a directed motion. The examples of such systems range from tissues [1], bacterial colonies [2], and people crowds [3] in nature to self-propelled microparticles [4] and robots [5] among man-made objects. The latter platform is especially attractive due to the possibility of tailoring the shape, motion profiles, and velocities of macroscopic robots in a much more simple and precise manner compared to microscopic or living systems. Despite various collective phenomena in active particles such as jamming [6] and topological edge state formation [7] have been implemented with robotic swarms, the formation of active crystals remains much less explored, and has been observed only in microparticles [4] for which a quantitative study of the crystallization dynamics renders challenging.

In the present paper, we realize a swarm of elongated self-propelled Swarmodroid robots [8] placed in a parabolic potential of the satellite antenna and extract the detailed information on the kinetics of crystal formation averaged over 300 independent experiments.

Experimental setup and results

Our experimental setup includes 45 bristle-bots having the size of 85×48 mm and based on the Swarmodroid platform [8], Fig. 1. Such robots are equipped with the QX-6A vibration motor and elastic bristles at the bottom which convert the motor vibration to a directed motion [9]. The robots include Robiton LP502020 rechargeable battery, TSOP4838 IR receiver allowing to turn the robots on and off and adjust their motion velocity, and ArUco marker placed atop of each robots' plastic body. These markers are recognized in the experimental recordings with the help of AMPy Python library (https://github.com/swarmtronics/AMPy) based on OpenCV. The videos are captured with Sony ZV-E10 HD-camera placed above the experimental area at the height of 152 cm. Finally, the robots are placed in the parabolic potential implemented as an aluminum satellite dish with dimensions 120×110×11 cm. Such smooth potential barrier prevents the condensation of robots at the abrupt borders [5] which, as we will demonstrate further, allows their slow condensation to the high-symmetry crystalline ground state instead of a rapid formation of an amorphous structure as in the case of jamming [6]. The reason for considering such elongated robots is twofold. First, the larger distance between pairs of bristles

at the front and back sides of the robots allows obtaining stable forward motion, while making symmetric circle-shaped robots move forward renders much more challenging. Second, as we will demonstrate further, breaking the rotational symmetry of robots leads to the formation of more complex structures not observed in the swarms of symmetric particles.

In the following, we place the robots in a random fashion inside the experimental area, see Fig. 1, *a*, while they are turned off. Then, at the timestamp $t = 0$ s, we simultaneously turn the robots on, making them move at the typical velocity of $v = 14$ cm/s and capture their motion during $T = 60$ s. Within the processing stage, positions of robots' centers and angular orientation of robots are extracted from the videos. The measurements are manually repeated 300 times for various random initial arrangements of the robotic swarm to obtain average dependencies of the characteristic quantities.

Figure 1 shows the evolution of a randomly arranged swarm, Fig. 1, *a*, upon turning the robots on. First, the robots start moving and orient their noses towards the edge of the potential, in accordance with one of the regimes considered in Ref.[10] for a single robot. As a result, they reach a steady mean radial location from the center of the potential corresponding to the distance at which the robots' self-propelling acceleration is compensated by their potential

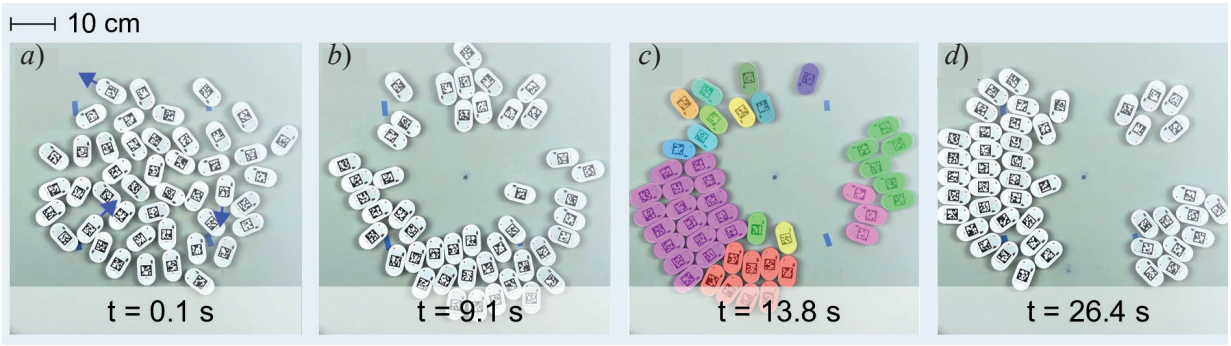

Fig. 1. Experimental demonstration of robotic swarm crystallization in the parabolic potential for a swarm of 45 robots. Blue dot at each panel denotes the center of the potential. Initial random arrangement of the robotic swarm (*a*). The arrows illustrate motion directions of several robots when they are turned on. The onset of clusterization characterized by multiple clusters of two to three aligned robots (*b*). The formation of a large densely packed hexagonal cluster. Different colors denote clusters of aligned touching robots (*c*). The evolution of the hexagonal cluster (*d*)

energy gradient, Fig. 1, *b*. At this point, they form an amorphous structure with a large number of small clusters. Upon further evolution, the robots adjust their locations and merge to densely packed clusters, as shown in Fig. 1, *c*. Finally, these stable crystalline clusters demonstrate some angular motion as a whole, with processes of absorbing or emitting single robots or small clusters. However, they were not transformed back to the amorphous phase throughout our experiments, facilitating the stability of such crystalline state of active particles, Fig. 1, *d*. It is seen that, in contrast to the particles of circular or spherical shape [4], the considered elongated robots form polycrystals consisting of several crystallites with different orientations of the main axes, see purple and red clusters in Fig. 1, *c*.

To describe the crystal formation dynamics, we consider several quantities shown in Fig. 2. The first one is the mean radial coordinate $\langle \rho(t) \rangle$ for all robots, Fig. 2, *a*. Next, we evaluate the mean traveled polar distance averaged over all robots $\langle \varphi_i(t) - \varphi_i(0) \rangle_i$ with

$$\varphi_i(t) = \sum\nolimits_{m \in frames[0...t]} | \varphi_{m+1} - \varphi_m |,$$

where φ_m is the polar angle for robot i at frame m and $\varphi_i(t)$ is the traveled angular distance, Fig. 2, *b*. To characterize the density of system packing, we calculate the mean number of robots in aligned touching clusters (mean cluster size, MCS) shown in Fig. 2, *c*. Finally, to quantify the formation of the triangular lattice, we evaluate the six-fold order parameter [11, 12] characterizing the emergence of the hexagonal close packing (i.e., the triangular lattice) $\psi_6 = \langle p_{6,i} \rangle_i$, where brackets denote the average over all robots with

$$p_{6,i} = \left| \frac{1}{6} \sum_{k \in N_i} e^{j6\theta_{ik}} \right|^2,$$

where N_i are indices of the six nearest neighboring robots to the i-th robot, j is the imaginary unit, and θ_{ik} is the angle between the vertical axis and the vector connecting centers of the i-th and k-th robots. In the case of the triangular lattice $\psi_6 \equiv 1$, while an amorphous system corresponds to $\psi_6 \equiv 0$. As robots have an asymmetrical shape, the maximum of ψ_6 corresponds to the triangular lattice with the aspect ratio 9/5. The results are shown in Fig. 2, *d*.

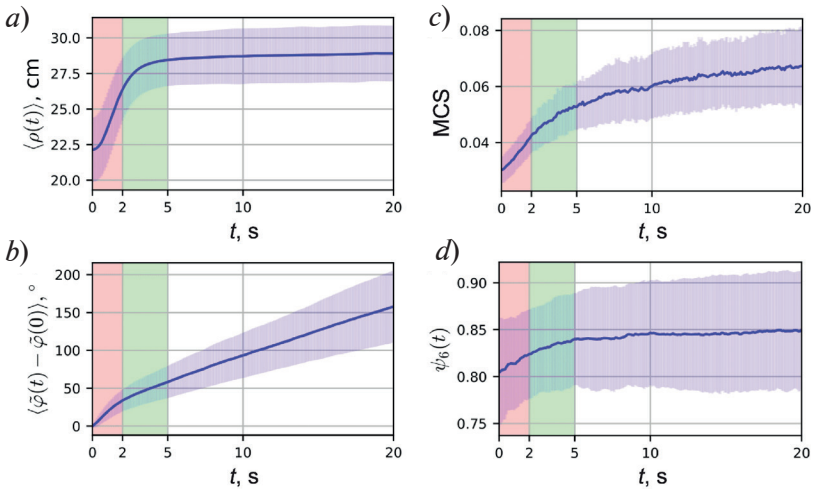

Fig. 2. Time dependencies of mean distance between the centers of robots and the center of the parabolic barrier (*a*); mean polar angle of the robots (*b*); mean number of touching robots in connected clusters (*c*); six-fold order parameter (*d*). The results are averaged over 300 realizations of the same experiment for different initial configurations of randomly arranged 45 robots. Shaded areas demonstrate the dispersion of the obtained quantities

As seen in Fig. 2, *a*, the mean radial distance of robots grows rapidly at the initial stage and then saturates, which corresponds to robots reaching the typical distance outlined earlier. In contrast, the mean angle continues to grow monotonically even after the formation of a triangular lattice (white region), Fig. 2, *b*, corresponding to the angular motion of the dense cluster as a whole. The mean cluster size and six-fold order parameter demonstrate a similar behavior: grow fast at the initial stage of a disordered system (red region), then slow their growth in the intermediate regime of amorphous packing (green region) and saturate upon the formation of crystalline structures (white region).

Moreover, the mean cluster size and the six-fold order parameter obey power laws during the crystal formation (prior their saturation) $\mathrm{MCS}(t) \approx 0.036t^{0.25}$ and $\psi_6 \approx 0.814t^{0.019}$, as demonstrated in Fig. 3.

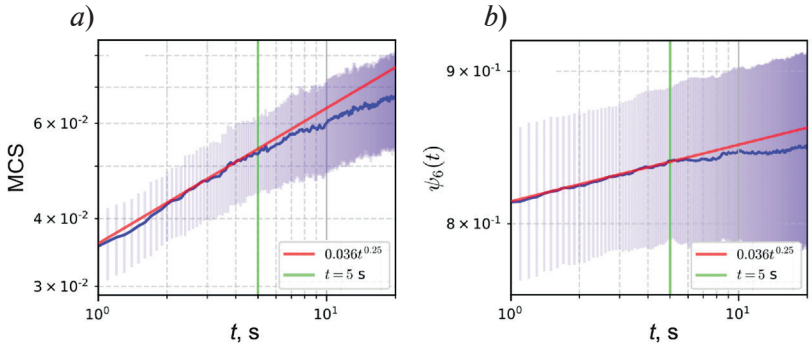

Fig. 3. Time-resolved evolution of MCS (blue line) (*a*). Time-resolved evolution of the parameter ψ_6 (blue line) (*b*). Red solid lines show the power-law approximations defined in the insets, and green lines highlight the characteristic times when such approximations are applicable

Conclusion

We studied experimentally the formation of crystals by swarms of self-propelled robots in a parabolic potential. Averaging the results over 300 realizations, we obtained time dependencies of characteristic quantities describing the crystallization and demonstrated power-law dynamics of the mean cluster size and the six-fold order parameter.

REFERENCES

1. **Balasubramaniam L., et al.,** Nature Materials, 20 (2021) 1156–1166.
2. **Avraham B., et al.,** Communications Physics, 3 (2020) 66.
3. **Silverberg J.L., et al.,** Physical Review Letters, 110 (2013) 228701.
4. **Ginot F., et al.,** Nature Communications, 9 (2018) 696.
5. **Deblais A., et al.,** Physical Review Letters, 120 (2018) 194501.
6. **Barois T., et al.,** Physical Review E, 99 (2019) 052605.
7. **Yang X., et al.,** Physical Review E, 101 (2020) 022603.
8. **Dmitriev A. A., et al.,** arXiv:2305.13510 (2023).
9. **Giomi L., et al.,** Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 469 (2013) 20120637.
10. **Dauchot O., Demery V.,** Physical Review Letters, 122 (2019) 068002.
11. **Strandburg K. J., et al.,** Springer Science & Business Media, (1992).
12. **Wang G., et al.,** Physical Review Letters, 126 (2021) 108002.

THE AUTHORS

BUZAKOV Mikhail K.
mikhail.buzakov@metalab.ifmo.ru
ORCID: 0000-0001-5309-8919

PORVATOV Vadim A.
eighonet@gmail.com
ORCID: 0000-0003-1950-9205

SMIRNOV Vyacheslav A.
v.smirnov@metalab.ifmo.ru
ORCID: 0000-0001-9378-573X

BURMISTROV Oleg I.
oleg.burmistrov@metalab.ifmo.ru
ORCID: 0000-0003-0083-6409

SENNIKOVA Daria V.
daria.sennikova@yandex.ru
ORCID: 0000-0003-1498-8091

PUHTINA Ekaterina M.
ekaterina.puhtina@metalab.ifmo.ru
ORCID: 0000-0002-1177-9748

MOLODTSOVA Anastasia A.
a.molodtsova@metalab.ifmo.ru
ORCID: 0000-0001-9635-5444

DMITRIEV Alexey A.
alexey.dmitriev@metalab.ifmo.ru
ORCID: 0000-0003-0022-6432

ROZENBLIT Alina D.
alina.rozenblit@metalab.ifmo.ru
ORCID: 000-0001-6745-4796

OLEKHNO Nikita A.
nikita.olekhno@metalab.ifmo.ru
ORCID: 0000-0002-9437-3320

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