Optimizing self-rotating bristle-bots for active matter implementation with robotic swarms

V A Porvatov, A D Rozenblit, A A Dmitriev, O I Burmistrov, D A Petrova, G Yu Gritsenko, E M Puhtina, E I Kretov, D S Filonov, A Souslov, and N A Olekhno

1 Moscow Institute of Physics and Technology, 141701 Moscow, Russia
2 National University of Science and Technology “MISIS”, 119991 Moscow, Russia
3 Public Joint Stock Company “Sberbank of Russia”, 117997 Moscow, Russia
4 ITMO University, 197101 Saint Petersburg, Russia
5 Lomonosov Moscow State University, 119991 Moscow, Russia
6 University of Bath, Bath, UK

E-mail: *olekhnon@gmail.com

Abstract. Robotic swarms have been recently explored as a versatile and scalable alternative to traditional microscale platforms for experimental studies of active matter. These robotic setups consist of either self-propelled or self-rotating particles. In the present paper, we develop and experimentally realize a swarm of self-rotating bristle-bots suitable for a wide range of active-matter experiments. We focus on optimizing the bristle-bot design and controlling the sliding friction between individual robots.

1. Introduction

The physics of active matter explores mechanical phenomena in non-equilibrium systems consisting of particles that individually convert their internal energy into mechanical work and motion. Typical examples of such systems include various micro- and nanoscale setups, ranging from bacterial colonies [1] and liquid crystals with molecular motors [2] to self-propelled colloidal particles [3, 4]. However, the complexity of conducting experiments at the microscale has recently resulted in the development of swarm-robotics platforms [5, 6, 7, 8], which offer an unprecedented degree of control over system parameters.

In the present paper, we consider a swarm of self-rotating bristle-bots. Optimizing the bristle-bot design, we define an optimal set of bristle parameters and construct a system with adjustable side friction between individual robots. Such a system can be used to study the mobility of individual robots upon the variation in their packing density and side friction, thus paving the way towards experimental studies of friction-assisted phase transitions in active matter.

2. Experimental setup

We aim to explore bulk active phases and transitions between them. To separate such bulk phenomena from boundary effects, we focus on systems with self-rotating robots in which both the number of robots and the confinement area shape can be varied. We realize experimentally the ensemble of 80 self-rotating bristle-bots vibrating at frequencies of approximately 60 Hz,
Figure 1. Examples of experimental setup with bristle-bots inside a circular boundary of diameters $d = 60$ cm (a) and $d = 45$ cm (b). (c,d) Post-processed images with connected clusters of robots shown by solid lines.

Figure 1(a,b). The vibration of an electric motor inside each robot is converted to a rotation around the robots’ center by a circularly shaped layer of elastic bristles at the bottom of each robot. The robots are 50 mm in diameter and consist of a 3D-printed body made of PLA plastic, a vibration motor, a rechargeable 3.7V battery, and a control circuit. The circuit allows turning the robots on and off with an infrared remote control.

Figure 2. Optimization maps for the Bflex bristles, showing (a) the distance $x$ travelled by the robot and (b) the self-rotation frequency $f$ for different bristle angles $\alpha$ (vertical axis) and thicknesses $h$ (horizontal axis) of elastic bristles.
Figure 3. Optimization maps for the PLA bristles, showing (a) the distance $x$ travelled by the robot and (b) the self-rotation frequency $f$ for different bristle angles $\alpha$ (vertical axis) and thicknesses $h$ (horizontal axis) of elastic bristles.

The motion of all the robots is captured by a camera and then analyzed with the help of deterministic algorithms from the OpenCV library in order to simultaneously track the triangle-shaped markers placed on top of every bristle-bot. Such an imaging allows us to capture the detailed kinematics of the system, Figure 1(c,d).

The applied approach to extracting the system’s kinematics is motivated by the properties of constructed setup. In particular, the proposed design of self-rotating bristle-bots leads to minor changes in the ensemble’s geometry during each time step between the consequent recorded frames. This feature of spatio-temporal locality was used in the nearest neighbor search algorithm in order to recover the robots’ trajectories. Moreover, the formation of connected clusters of robots in the ensemble can be extracted from the tracking information using collision graphs and further explored by breadth-first search, as shown in Figure 1(c,d).

3. Bristle-bot design optimization
The effects of bristles shape on the movement pattern of individual bristle-bots have been explored theoretically and experimentally in the case of self-propelled bristle-bots [9] and driven self-rotators [10]. To optimize the bristles for our particular design of self-rotating bristle-bots, we perform a set of experiments varying the shape and thickness of bristles and considering different bristle materials.

We study 48 realizations including straight-line bristles composed of resin-like Bflex material,
Figure 4. (a) Top view schematics of the bristle-bots covered with different ribbons with angles $\beta = 30^\circ$, $\beta = 60^\circ$ and $\beta = 90^\circ$, respectively. (b) Images of experimentally fabricated bristle-bots corresponding to panel (a). (c) Photo of three interacting bristle-bots with the maximal value of the effective side friction ($\beta = 90^\circ$).

Figure 2, and PLA plastic, Figure 3, with angles of $\alpha = 0^\circ$ up to $\alpha = 35^\circ$ with the step $5^\circ$. According to the properties of each material, we use thicknesses $h = 0.4$, 0.6, and 0.8 mm for PLA and $h = 0.8$, 1.0, and 1.2 mm for Bflex. We optimize two parameters: the traveled distance of each robot (which should be minimized for self-rotating robots) and the self-rotation frequency (which should be maximized). In order to obtain more representative results, we perform averaging over 3 independent realizations of each experiment considering different bristle-bots. After this stage, we apply OpenCV library to extract required magnitudes from the captured videos.

As seen from Figure 2, in the case of Bflex bristles the optimal realization with $\alpha = 5^\circ$ and $h = 1.2$ mm corresponds to 1.46 self-rotations per second at travelled path of 97.61 cm during the 30-second observation time. However, these results are outperformed by the PLA bristles, as seen from Figure 3. Indeed, the PLA bristles with $\alpha = 10^\circ$ and $h = 0.4$ mm allow achieving 1.8 rotations per second at the displacement of 63.85 cm during the 30-second observation time. Thus, we select this set of bristle parameters for the following realization of the bristle-bot swarm.

4. Adjustment of side friction between robots

Next, we focus on controlling the side friction between two (or more) individual bristle-bots. To proceed, we consider interacting rotating particles in the form of trapezoidal gears, schematically depicted in Figure 4(a). The effective friction coefficient is controlled by the angle at the base of the trapezoid $\beta$, with the limit of $\beta = 90^\circ$ corresponding to infinite effective friction. For the first tests, we fabricated a set of scalloped PLA ribbons with a trapezoidal meander profile wrapped around the side surface of each robot. Creating ribbons with angles $\beta$ in the range $20^\circ \leq \beta \leq 90^\circ$ with step $10^\circ$, we optimize the trapezoids' geometry in different ways so as to preserve the period $T \approx 5.7$ mm and equal dimensions of the small base and the meander gap. Thus, for $\beta = 20^\circ...70^\circ$, we fix bases $a \approx 1.0$ mm and $b \approx 4.7$ mm along with changing the trapezoid height $H \approx 0.6...5$ mm, whereas for $\beta = 80^\circ$, we set different dimensions of the bases $a \approx 2.0$ mm, $b \approx 3.7$ mm and the height $H = 5$ mm. Finally, for the rectangle meander ($\beta = 90^\circ$), we set $a = b \approx 2.5$ mm and $h = 2$ mm. Thus, we make a gap larger than the base of
the rectangle since the obtained “gears” otherwise may not fit each other due to imperfections of the 3D-printing process. Figure 4(b) shows the fabricated bristle-bots covered by ribbons of three different types. If the bristle-bots rotate in the same direction, then the ribbons with larger angles $\beta$ may cause pronounced cluster formation, while the ones with small angles provide weaker interaction between particles. An example of interaction between three bristle-bots is shown in Figure 4(c).

5. Conclusion
We have developed, optimized, and experimentally realized the active matter setup consisting of self-rotating bristle-bots. The implemented setup allows us to study the effects of changing the side friction between particles on phase formation in active matter, an exciting topic which has only recently begun to be explored [11, 12].

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