Emergent Mechanism Design via Robot Swarms

Annalisa T. Taylor, Thomas A. Berrueta, Todd D. Murphey

***Abstract*—Most decentralized robot swarms achieve tasks by specifying local rules designed to prevent agents from disrupting one another. In turn, such agents spend a substantial portion of their computational budget avoiding collisions and unstructured interactions. However, recent work has found that task-capable emergent behaviors can emerge from such messy physical interactions. In this sample from our on-going work we suggest that instead of designing swarms to avoid physical interactions, tasks can be achieved by harnessing the work generated by a decentralized collective of stochastically colliding agents. We explore the idea of building mechanisms (e.g., ratchets, pulleys, belt drives) out of the self-organized states of robotic active matter. Taking advantage of known connections between collision-driven systems and thermodynamics, we are able to quantify the rate of work generation of these emergent system states. Then, we may design tools and mechanisms that harness the work done by the swarm towards achieving desired tasks. To ensure that desirable configurations with respect to a given task form consistently, we propose an algorithm to achieve closed-loop work generation by locking the system into beneficial self-organized configurations. Here, we outline plans to produce reliable, emergent mechanisms from the interactions of colliding agents.**

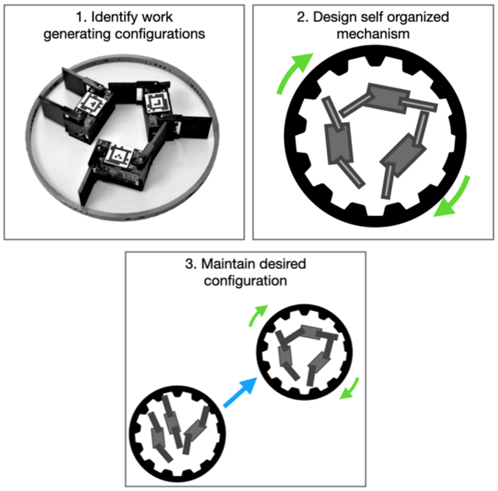

Fig. 1. **Mechanism design via rattling-based behavioral annealing.**

To achieve complex behaviors such as shape formation, swarms of robots typically follow local and decentralized rules that deterministically choreograph the movements of each agent. The ways in which agents are (dis)allowed to interact are crucial to task success—if an agent takes an action out of step from its neighbors, the collective task may fail entirely. As such, collisions and unstructured interactions between agents tend to be avoided at all costs, leading to substantial computational expenditures for this purpose. In this work, rather than wasting time and computational resources on collision avoidance, we suggest that embracing collisions and physical interactions can nonetheless lead to nontrivial swarm task-capability. To this end, we explore useful work generation in a swarm of colliding robots called *smarticles* [6].

Each smarticle is comprised of a rectangular body lying on a flat surface and two flapping arms that cannot contact the ground. Although an individual smarticle is immotile, a group of them confined to a small area interacts persistently through collisions and produces emergent behaviors [2, 5]. However, controlling such a robot collective and producing useful work remains an open problem. In this manuscript, we focus on collectives of three smarticles enclosed in a ring as shown in Fig. 1. This system has been shown to exhibit persistent “dances” that emerge spontaneously from the collisions caused by the movement of each smarticle’s arms [2]. These dances are self-organized dynamical attractors of the collective and are a function of the pattern of arm movements, also known as the system’s “drive pattern.”

To develop control and design principles for extracting useful work from colliding robot collectives, we require a theoretical framework from which to build as a starting point. Statistical mechanics from its inception has been concerned with elucidating the behaviors of colliding elements (i.e., atoms and particles), as well as their dissipation and work generation, and its insights extend to macroscopic collision-driven systems such as billiards [1]. The smarticle system, whose quasi-random diffusive behavior was characterized in [5], is an ideal candidate system to explore the potential of thermodynamics-based swarm control strategies. In particular, we propose that two key results in nonequilibrium thermodynamics can be applied to ensure robust work generation that may be harnessed towards task-capability.

The first enabling result is the development of *rattling theory* [2]. Rattling theory describes the way in which correlations among disordered degrees of freedom in driven systems determine the magnitude of system-level fluctuations. The magnitude of these fluctuations determines the stability of system configurations. Hence, rattling theory predicts which configurations the system is likely to evolve towards and remain in for long periods of time. Moreover, the theory predicts that complex systems *spontaneously* evolve towards configurations that minimize the magnitude of such fluctuations, also known as the low rattling selection principle. To quantify the magnitude of these fluctuations at a given configuration, we can compute rattling $\mathcal{R}(q)$—from which the theory derives its name—in the following way:

$$\mathcal{R}(q) = \frac{1}{2} \log \det \mathcal{C}(q), \tag{1}$$

where q is a configuration variable (e.g., coordinates $[x, y, \theta]$

of all smarticles), and $\mathcal{C}(q)$ is the system's configuration-space covariance matrix sampled over short trajectories initialized at q. Using $\mathcal{R}(q)$ the low rattling selection principle is

$$p_{ss}(q) \propto e^{-\gamma \mathcal{R}(q)}, \tag{2}$$

with γ as a system-specific constant of order 1. This closed form relationship between the nonequilibrium steady-state and rattling allows one to quantify the likelihood of system configurations and thus characterize the emergence of self-organized system configurations. It is important to note that for a given drive pattern, a complex system may produce a variety of self-organized states, which themselves are subject to change if a different drive pattern is applied.

Equipped with a way to numerically identify emergent nonequilibrium system configurations (e.g., the dances shown in [2]), the second thermodynamic result needed to enable robust collision-driven swarm work generation is the Crooks Fluctuation Theorem (CFT) [3]. The CFT provides a closed-form relationship between the irreversibility of transitions between system configurations and the work that must be done in order for that transition to be possible. This theorem has been greatly extended since its introduction. Notably, work in [4] provides a lower bound on the amount of work that must be generated for a nonequilibrium system to remain at a given state. Then, by combining the CFT (and its extensions) with rattling theory we arrive at the following conclusion: complex nonequilibrium systems spontaneously evolve towards self-organized states, which themselves must persistently do work on their environments in order to be maintained. Put plainly in terms of our smarticle system, we are simultaneously guaranteed that the swarm will evolve to self-organized configurations *and* that those configurations will generate a net amount of work—precisely the conditions we require to enable collision-driven task-capable behaviors.

Given a guaranteed source of work generation in our swarm of colliding agents, our final task is to harness this energy towards desirable outcomes. However, while the CFT and rattling theory guarantee that our systems will be able to produce work, they say nothing about the character of the work generated. Moreover, both the amount and the type of work generated may vary from low-rattling configuration to low-rattling configuration. For example, in our three-smarticle system certain self-organized states lead to work generation via linear displacements whereas others produce a net angular momentum. While both of these configurations produce work, the mechanisms needed to harness said work into task-capability may have to be designed differently. Momentarily sidestepping the issue of the configuration-dependent character of the work generated by the system, we may consider designing a tool that harnesses the net angular momentum of the smarticle swarm to actuate simple mechanisms such as a belt drive transmission or a pulley. One minimal design that leverages the rotational energy of this spontaneously arising configuration is a planetary gear, as shown in Fig. 1. By harnessing this rotational energy, a smarticle-actuated planetary gear system could potentially power a mechanical or electrical device.

Algorithm 1 Rattling-Based Behavioral Annealing

```
Run smarticle system with desired drive pattern
Allow it to settle into a low-rattling configuration
Determine if type of work generation matches desired mechanism
while Work is not of correct type do
    Increase drive entropy for some duration
    Decrease drive entropy
    if Work is of correct type then
        Break
    end if
end while
Exploit mechanical work in current configuration
```

Although the three smarticle system has been shown to reliably self-organize into low-rattling configurations, due to intrinsic nondeterminism we cannot *a priori* specify which configuration that will be. Some of the states the system may find itself in will be irrelevant to a candidate mechanism, as was mentioned above, and thus have no relative value in achieving a chosen task or goal. Hence, it is necessary to be able to not only observe the prevalence and persistence of low-rattling configurations, but also to influence their stability in order to guide the system towards beneficial configurations. As shown in [2], one way to do this is by raising drive entropy—or, in other words, move the smarticle arms completely randomly when the system is in an undesirable configuration. Raising drive entropy leads to a direct increase in the rattling of a configuration, which effectively destabilizes it by increasing the likelihood of leaving it. Thus, by increasing drive entropy we may not be able to specify desirable states, but we may specify the undesirable ones and leave them.

Using this knowledge, we may construct an algorithm that would guarantee desirable work generation with respect to a specified task. In Algorithm 1 we propose such an algorithm, which we term *rattling-based behavioral annealing*. Remarkably, the proposed algorithm is very similar to an annealing schedule with drive entropy playing the role of temperature, and indeed at a high-level it operates on similar principles. The crucial insight, as is the case in annealing processes, is that when we raise drive entropy the system explores a greater diversity of configurations in which to settle, whereas without raising drive entropy the system may remain stuck in a (task-irrelevant) low-rattling state. By executing this rattling-based annealing process multiple times, we can iteratively explore the system's low-rattling states until we eventually find the desired state.

Robots and swarms have for long been design to avoid unstructured and unpredictable interactions. While this has produced demonstrable progress, designing systems to explicitly avoid the emergence of self-organized behaviors is a missed opportunity for the development of future autonomy. By exploiting thermodynamics, future swarms may become task-capable despite appearing disorderly.

REFERENCES

[1] Timothy Chumley, Scott Cook, and Renato Feres. From billiards to thermodynamics. *Computers & Mathematics with Applications*, 65(10):1596–1613, 2013.

[2] Pavel Chvykov, Thomas A Berrueta, Akash Vardhan, William Savoie, Alexander Samland, Todd D Murphey, Kurt Wiesenfeld, Daniel I Goldman, and Jeremy L England. Low rattling: A predictive principle for self-organization in active collectives. *Science*, 371(6524):90–95, 2021.

[3] Gavin E Crooks. Entropy production fluctuation theorem and the nonequilibrium work relation for free energy differences. *Physical Review E*, 60(3):2721, 1999.

[4] Jordan M. Horowitz, Kevin Zhou, and Jeremy L. England. Minimum energetic cost to maintain a target nonequilibrium state. *Phys. Rev. E*, 95:042102, Apr 2017. doi: 10.1103/PhysRevE.95.042102. URL https://link.aps.org/doi/10.1103/PhysRevE.95.042102.

[5] W. Savoie, T. A. Berrueta, Z. Jackson, A. Pervan, R. Warkentin, S. Li, T. D. Murphey, K. Wiesenfeld, and D. I. Goldman. A robot made of robots: Emergent transport and control of a smarticle ensemble. *Science Robotics*, 4(34), 2019. doi: 10.1126/scirobotics.aax4316.

[6] William Carey Savoie. *Effect of shape and particle coordination on collective dynamics of granular matter*. PhD thesis, Georgia Institute of Technology, 2019.