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SCHOOL OF PHYSICS

FINAL YEAR PROJECT INTERIM REPORT

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1 Introduction

In recent years, there has been increasing research into the collective behaviour of active matter in non-equilibrium systems. Emergence of self-propelled agents is observable in many natural systems including schools of fish, flocks of birds, crowds of people, and bacterial colonies. In physics, emergence occurs when a system of individual agents acts according to a set of rules and the behaviour of their neighbouring agents to form a collective body. In the context of biology, the study of the behaviour of active matter is key for advancing our knowledge of cellular and bacterial dynamics. The study of this has important applications in medicine, including furthering our understanding of bacterial infections and contamination [1], and the development of life-like non-equilibrium materials [2]. The reasons for emergence occurring so frequently in nature is an ongoing area of study, however it has been seen that swarming has various evolutionary advantages. Research has suggested that in bacteria, swarming provides a higher probability of colony survival and success in fighting antibiotics [1]; in birds, flocking provides increased protection from predators, allowing individuals to spend less time on the lookout for danger and more time feeding [3]. The growing research on emergent systems highlights the advantages of swarm behaviour and shows promise for applications in other areas of development such as technology and robotics. These swarms found so commonly in nature, emerging through biological evolution and natural selection, are testament to the effectiveness of this emergent behaviour, suggesting that it is an effective means of information transmission and efficiency. Swarm robotics is an increasing area of interest and development, founded on the assumption that applying the behavioural principles observed in natural emergent systems to robotics, will result in robotic swarms with efficiency and stability similar to the swarms so frequently found in nature [4]. This research project explores the key principles of self-organisation and applies this theory to a system of simplistic swarm robots, Kilobots. The Kilobot is a popular model of swarming robot developed at Harvard University by the Self-Organizing Systems Research Group, and manufactured by K-team [5]. Swarm robotics is used to explore the ability of multi-agent systems to complete tasks as a unit. This is especially helpful for tackling jobs that cannot be completed by an individual, or that is more effectively completed by a collaborative group [6]. Similar to flocks and swarms present in nature, a robotic swarm is more capable of completing complex tasks than individual agents through the utilisation of neighbour-to-neighbour interactions and information transmission between individuals, resulting in a highly organised and adaptable system [7]. Their excellent efficiency, organisation, and adaptability, paired with their sensing and communication abilities, swarm robots show great potential for a multitude of applications. Some examples of the uses of swarm robots include exploring and mapping large or remote areas, agriculture, and military/defence, as well as being a useful means to model nature swarms. Features that enable swarm robots to complete tasks, such as the aforementioned examples, more efficiently and successfully than a group of independent robots are their scalability, redundancy, and adaptability. Scalability allows the agents to cover a large area, allowing for vast exploration in less time - which is particularly beneficial for more efficient exploration and agriculture - and if needed, more robots can be added without disruptive changes to the system. Redundancy is especially relevant for completing more dangerous tasks such as in treacherous terrain or military operations, reducing the need to put people or animals in high risk situations, and the loss or failure of a robot does not disrupt the functioning of the rest of the system. Of course, adaptability is vital for any system to work efficiently and successfully, adjusting strategies and distribution of roles depending on the environment, threats, and tasks. Within this project, the adaptability of a system to external stimuli is of particular interest, studying the behaviour of the system when introduced to a barrier. This is investigated through the use of a minimal computational model and Kilobots, changing the conditions of the system to examine the agents' response to a barrier. One of the main areas of study in this project is observing the phase transitions present in self-organising systems and evaluating how the parameters of the system affect its behaviour. The accumulation of agents at the boundary of a barrier can be compared to liquid particles spreading over and wetting a surface. This liquid-gas transition can be used to describe the phase transition observed in the Vicsek model and how this varies with the system parameters. The type of phase transition that most accurately describes the behaviour observed in the Vicsek model is an area of discourse between researchers, with it commonly being described as an order-disorder phase transition. This project investigates the transitions seen in the model and aims to identify the threshold of the phase separation for varying system conditions; it also compares the order-disorder bulk phase transition to the liquid-gas surface phase transition wetting, particularly when introducing a barrier into the environment.

2 Background

2.1 The Vicsek Model

The model used to study the collective behaviour of active matter is the Vicsek model, which is arguably one of the simplest theoretical models for simulating collective motion. This model shows the motion of N self-propelled particles transitioning from disordered to ordered collective motion through self-organisation via local interactions. The particles follow a single rule to perform this transition: at each time step, Δt, each particle, moving with a constant velocity v, aligns itself with the average orientation of the particles in its neighbourhood of radius r, curbed by some added random noise η [8]. At each time step, the position x and orientation θ of the i^{th} particle is updated according to

$$\boldsymbol{x}_i(t+\Delta t) = \boldsymbol{x}_i(t) + \boldsymbol{v}_i \Delta t \quad (1)$$

$$\theta(t+\Delta t) = \langle \theta(t) \rangle_r + \eta \quad (2)$$

respectively, where $\langle \theta(t) \rangle_r$ is the average orientation of the particle's neighbours [8]. The pre-existing code from [9] was adapted and set up to simulate 5000 particles in a box of an arbitrary linear length 50 with periodic boundary conditions (code available on Github). The particles are represented as quiver vectors, with their colour denoting their orientation, as can be seen in figure 1. It can be expected that at the end of the simulation, the particles will align and hence be the same colour. This global order of the system is quantitatively evaluated through calculations of the average alignment of the particles using

$$\phi(t) = \frac{1}{N} \sum_{i=1}^{N} \hat{e}_i(t) \quad (3)$$

where $\phi(t)$ is the global order, N is the number of particles, and $\hat{e}_i(t)$ is the orientation of the particle. To improve the runtime for larger numbers of particles, the Vicsek model was amended to only check the orientation of neighbours within a square cell of linear size r, and the high performance Python compiler Numba [10] was used to parallelise the simulation, as all particle positions and orientations are updated synchronously. The behaviour of the system primarily depends on the noise amplitude η, the particle speed v, and the density of the particles $\rho = \frac{N}{L \times L}$. In this simulation, the initial parameters were set to be $\eta = 0.2$, $\rho = 2.0$, $r = 1.0$, and the position and orientation of the particles were randomly generated in the box at time $t = 0$, with the same speed v. In the simulation, a bulk phase transition can be observed as the particles align themselves with one another, resulting in ordered motion in the bulk of the system. The transition between disordered and ordered motion is dependent on the amplitude of the noise and the density of the particles, as the information between neighbours needs to be able to travel through all the particles in the system for them to coordinate their movement [11]. This means that high levels of noise disturb the information transfer, resulting in disordered motion as the particles are unable to coordinate with one another. As the noise is lowered below a specific threshold, the phase transition from disordered to ordered motion can occur as the particles are able to communicate and align with their neighbours. The same principles apply when considering the density of the particles in the system - with too few particles, their neighbours are not within the interaction radius and they cannot communicate with one another. At higher particle densities and lower noise amplitudes, a flocking phase with high global polar order emerges, characterized by organized, high-density bands of particles that propagate through the box, spanning its width [12][13]. The Vicsek model can also be accurately described by a liquid-gas surface phase transition, as both the bulk phase transition and the surface phase transition highlight the interplay between local interactions and collective behaviour. To further visualise the surface phase transition, the Vicsek model was modified to include an attractive barrier within the box, as shown in figure 4. The particles accumulate on the boundary of the barrier, aligning and creating ordered motion at its edges. The accumulation of particles at the boundary of the barrier is comparable to liquid particles spreading over, and hence wetting, a surface.

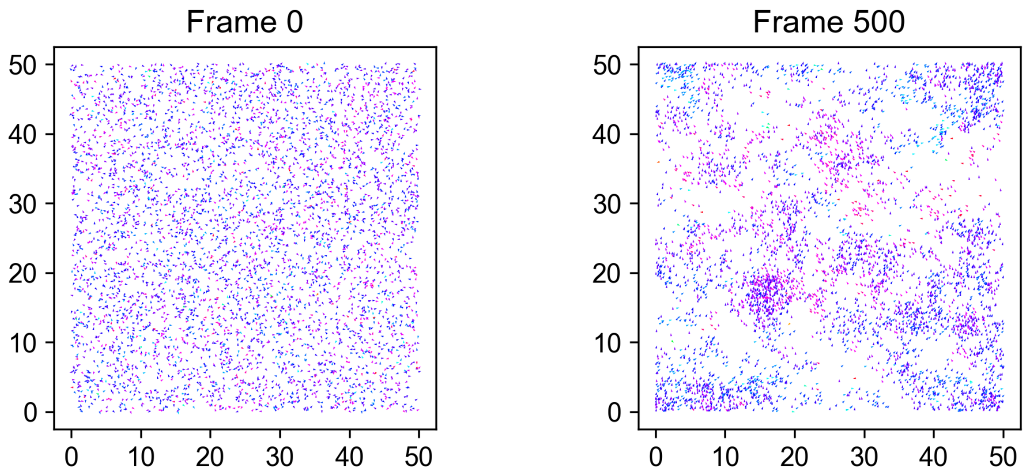

Figure 1: Initial and final position of 5000 self-organising particles in a 50 x 50 box after 500 iterations.

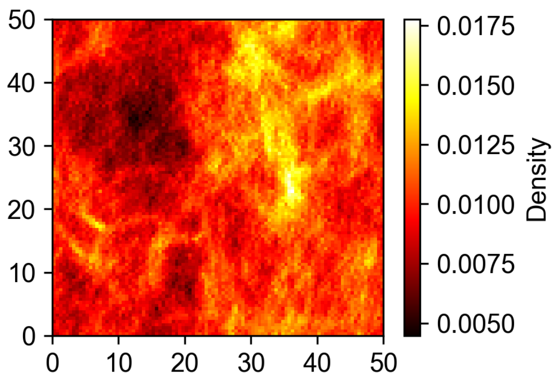

Figure 2: Particle density map of 5000 self-organising particles in a 50 x 50 box.

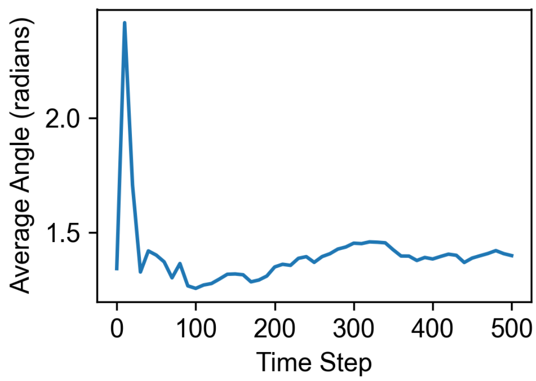

Figure 3: Angle alignment of 5000 self-organising particles in a 50 x 50 box.

2.2 Kilobots

The principles studied in the Vicsek model were applied to a more complex physical model, Kilobots. Kilobots were designed with the aim to keep the cost low and assembly simple to make large-scale swarm robotics more accessible to researchers. Despite their simplistic nature and affordability, Kilobots are equipped with differential drive, on-board computation power, and neighbour-to-neighbour communication and sensing capabilities. The robots achieve this through the vibration of two motors that allow them to shuffle across a surface on three rigid legs, and an infrared transmitter and receiver to detect the distance to their neighbours [14].

3 Preliminary Results

3.1 Vicsek Model

The Vicsek model clearly demonstrates the transition from disordered to ordered motion through collective behaviour, with alignment and the formation of high-density bands visible in figure 1. This banding is further shown in the particle density map in figure 2, with brighter

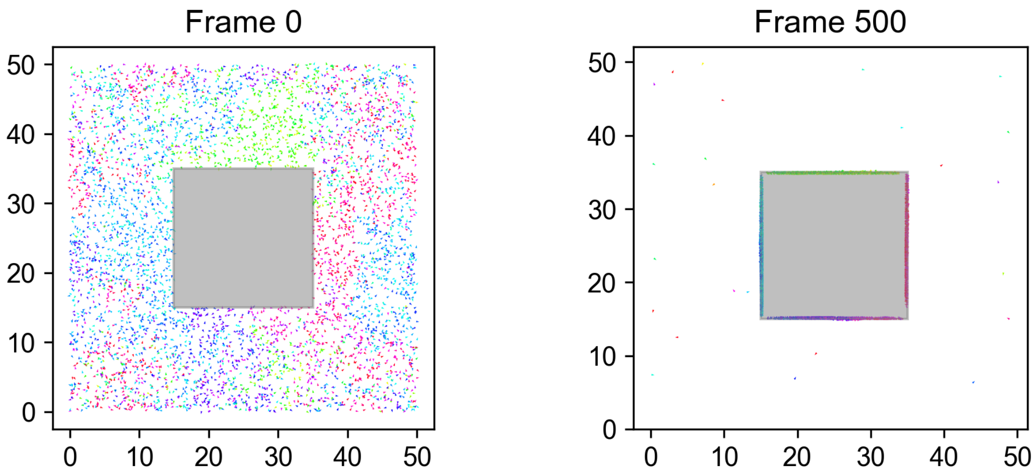

Figure 4: Initial and final position of 5000 self-organising particles in a 50 x 50 box with an attractive barrier after 500 iterations.

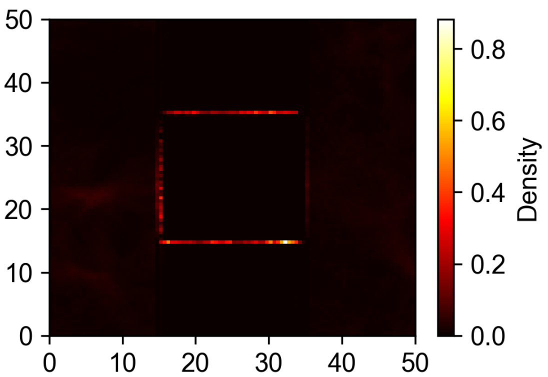

Figure 5: Particle density map of 5000 self-organising particles in a 50 x 50 box with an attractive barrier.

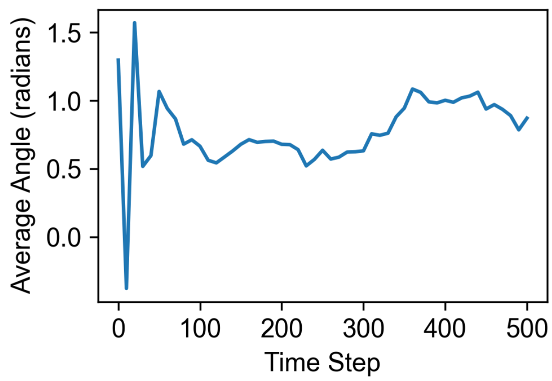

Figure 6: Angle alignment of 5000 self-organising particles in a 50 x 50 box with an attractive barrier.

yellow regions representing a high density of particles. Within these bands, the particles are highly synchronised in their movement and alignment, and despite the particles outside of the high-density regions, their is strong net alignment in the system. This is quantitatively described in figure 3, with the plot of average alignment showing a more smooth and flat line as the simulation progresses over time. The initial average alignment demonstrates an extremely steep and jagged line as the particles attempt to orient themselves with their neighbours that are pointing in an array of different directions. It can be seen that once the particles begin to align with one another, the system quickly determines a more unanimous orientation and reaches a more consistent state of alignment.

3.2 Barrier Vicsek Model

From figure 4, it can be seen that the edited Vicsek model with the added attractive barrier does not show banding as in figure 1, but instead demonstrates that the particles follow the motion of their neighbours and, as a result, end up gathering at the edges of the barrier. This is exaggerated by the plot of particle density in figure 5. This density map does not provide much information about the movement of the particles around the barrier, only showing the high density of particles gathered at the barrier boundary. This is to be expected due to the attractive nature of the barrier and the very low density of particles remaining away from the barrier. Despite the particles aligning and forming ordered motion at the edges of the barrier, the plot of particle alignment in figure 6 indicates that the particles have greater difficulty aligning with one another when there is an obstacle. From the steep peak at the beginning of the simulation followed by less extreme fluctuations, it can be seen that the particles begin to synchronise quickly. The variations in alignment seen as time goes on are likely due to the particles joining and leaving the edges of the barrier from different sides. It is very unlikely that the particles will ever be perfectly aligned in this variation of the Vicsek model, as the particles accumulate at different sides of the barrier resulting in variations in orientation of the order of 90°.

4 Discussion

The results show that the Vicsek model is an accurate tool for producing simulations of the collective motion of self-organising particles, including for large system sizes and changes to the environment. As expected from equation 2, the noise parameter prevents perfect alignment of the system, which is evident in the regular variability in the average alignment of the particles. The amplitude of noise and particle density, at $\eta = 0.2$ and $\rho = 2.0$ respectively, gives rise to easy alignment and formation of high-density bands while providing a low level of randomness to the system, making it more realistic and comparable to natural instances of collective motion. These moving bands are a convincing model of flocking behaviour, similar to those observed in bird flocks, with the particles inside the higher density region of the band demonstrating ordered motion and the particles in the low density areas outside the band performing random walks [15]. The high order ϕ within the bands, mixed with the low ϕ outside the bands (and the randomness attributed to noise) results in the bands gradually evolving and changing, evident in both the simulation and the alignment plot (figure 3). This principle also applies to the Viscek model with the attractive barrier - to some regard. The particles gathered on one of the sides of the barrier demonstrate ordered motion, giving a high ϕ, whilst the particles that are in the low-density region away from the barrier perform random walks, resulting in disordered motion and a low ϕ. With this logic, it would be expected that this alignment plot would be similar to the plot for the standard Vicsek model, however figure 6 is distinctly different from figure 3. This is largely due to the fact that the particles are attracted to different sides of the barrier, shown in figure 5, dividing the system into four groups of different orientations, but with each group displaying ordered motion. In addition to this, the noise in the system causes particles to leave the barrier and begin travelling in the low-density region in a vastly different direction; due to the collective behaviour of the particles, occasionally a large group of particles will simultaneously leave the barrier before rejoining the high-density area at a different edge. These situations result in significant changes in the global order of the system, explaining some of the more drastic fluctuations seen in the alignment plot in figure 6.

5 Conclusion

The results obtained from this investigation into the efficacy of studying self-organisation using the Vicsek model, suggests that it is suitable for modelling the behaviour of self-propelled polar agents in response to different system parameters and environmental changes. The Vicsek model, albeit simplistic, demonstrates potential for studying the collective behaviour of natural instances of collective motion, such as bird flocks, particularly due to its adaptability and inclusion of noise and density parameters. In this project the noise and particle density of the system could be explored further to evaluate the thresholds of the ordered, disordered, and flocking phases. Understanding the phase transitions involved and their boundaries is necessary to transfer the principles of the Vicsek model to other systems, such as the Kilobots. Another aspect of the Vicsek model to look into is the conditions of the barrier and the way that the particles respond to it. Using a repulsive barrier instead of an attractive one would provide more insight into the behaviour of the system, allowing for the particles to continue to move around it. It would be interesting to see how the particles navigate the barrier and if it impacts the global order or phase thresholds of the system. This research would support the progression of robot swarms, improving their navigation of obstacles and collision avoidance. This project demonstrates the applicability of active matter research, using natural systems to inform synthetic systems, opening doors to advancements in robotics and material development [2].

References

[1] Igor S. Aranson. "Bacterial active matter". en. In: *Reports on Progress in Physics* 85.7 (June 2022). Publisher: IOP Publishing, p. 076601. ISSN: 0034-4885. DOI: 10.1088/1361-6633/ac723d. URL: https://dx.doi.org/10.1088/1361-6633/ac723d.

[2] Daniel Needleman and Zvonimir Dogic. "Active matter at the interface between materials science and cell biology". en. In: *Nature Reviews Materials* 2.9 (July 2017). Publisher: Nature Publishing Group, pp. 1–14. ISSN: 2058-8437. DOI: 10.1038/natrevmats.2017.48. URL: https://www.nature.com/articles/natrevmats201748.

[3] Thomas Caraco, Steven Martindale, and H. Ronald Pulliam. "Avian flocking in the presence of a predator". en. In: *Nature* 285.5764 (June 1980). Publisher: Nature Publishing Group, pp. 400–401. ISSN: 1476-4687. DOI: 10.1038/285400a0. URL: https://www.nature.com/articles/285400a0.

[4] Thomas Schmickl et al. "Two different approaches to a macroscopic model of a bio-inspired robotic swarm". In: *Robotics and Autonomous Systems* 57.9 (Sept. 2009), pp. 913–921. ISSN: 0921-8890. DOI: 10.1016/j.robot.2009.06.002. URL: https://www.sciencedirect.com/science/article/pii/S0921889009000815.

[5] Fredrik Jansson et al. *Kilombo: a Kilobot simulator to enable effective research in swarm robotics*. arXiv:1511.04285 [cs]. May 2016. DOI: 10.48550/arXiv.1511.04285. URL: http://arxiv.org/abs/1511.04285.

[6] Levent Bayındır. "A review of swarm robotics tasks". In: *Neurocomputing* 172 (Jan. 2016), pp. 292–321. ISSN: 0925-2312. DOI: 10.1016/j.neucom.2015.05.116. URL: https://

www.sciencedirect.com/science/article/pii/S0925231215010486.

[7] Ying Tan and Zhong-yang Zheng. "Research Advance in Swarm Robotics". In: *Defence Technology* 9.1 (Mar. 2013), pp. 18–39. ISSN: 2214-9147. DOI: 10.1016/j.dt.2013.03.001. URL: https://www.sciencedirect.com/science/article/pii/S221491471300024X.

[8] Tamás Vicsek et al. "Novel Type of Phase Transition in a System of Self-Driven Particles". en. In: *Physical Review Letters* 75.6 (Aug. 1995), pp. 1226–1229. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.75.1226. URL: https://link.aps.org/doi/10.1103/PhysRevLett.75.1226.

[9] Turci Francesco. *Minimal Vicsek model in Python*. en. June 2020. URL: https://francescoturci.net/2020/06/19/minimal-vicsek-model-in-python/.

[10] Siu Kwan Lam, Antoine Pitrou, and Stanley Seibert. "Numba: a LLVM-based Python JIT compiler". In: *Proceedings of the Second Workshop on the LLVM Compiler Infrastructure in HPC*. LLVM '15. New York, NY, USA: Association for Computing Machinery, Nov. 2015, pp. 1–6. ISBN: 978-1-4503-4005-2. DOI: 10.1145/2833157.2833162. URL: https://dl.acm.org/doi/10.1145/2833157.2833162.

[11] Francesco Ginelli. "The Physics of the Vicsek model". en. In: *The European Physical Journal Special Topics* 225.11-12 (Nov. 2016), pp. 2099–2117. ISSN: 1951-6355, 1951-6401. DOI: 10.1140/epjst/e2016-60066-8. URL: http://link.springer.com/10.1140/epjst/e2016-60066-8.

[12] Alexandre P. Solon, Hugues Chaté, and Julien Tailleur. "From Phase to Microphase Separation in Flocking Models: The Essential Role of Nonequilibrium Fluctuations". In: *Physical Review Letters* 114.6 (Feb. 2015). Publisher: American Physical Society, p. 068101. DOI: 10.1103/PhysRevLett.114.068101. URL: https://link.aps.org/doi/10.1103/PhysRevLett.114.068101.

[13] Aitor Martín-Gómez et al. "Collective motion of active Brownian particles with polar alignment". en. In: *Soft Matter* 14.14 (Apr. 2018). Publisher: The Royal Society of Chemistry, pp. 2610–2618. ISSN: 1744-6848. DOI: 10.1039/C8SM00020D. URL: https://pubs.rsc.org/en/content/articlelanding/2018/sm/c8sm00020d.

[14] Michael Rubenstein, Christian Ahler, and Radhika Nagpal. "Kilobot: A low cost scalable robot system for collective behaviors". In: *2012 IEEE International Conference on Robotics and Automation*. ISSN: 1050-4729. May 2012, pp. 3293–3298. DOI: 10.1109/ICRA.2012.6224638. URL: https://ieeexplore.ieee.org/abstract/document/6224638.

[15] Hugues Chaté et al. "Collective motion of self-propelled particles interacting without cohesion". en. In: *Physical Review E* 77.4 (Apr. 2008), p. 046113. ISSN: 1539-3755, 1550-2376. DOI: 10.1103/PhysRevE.77.046113. URL: https://link.aps.org/doi/10.1103/PhysRevE.77.046113.