EXPERIMENTAL MEASURE OF PRESSURE IN ACTIVE MATTER

MSc Project - Stage II

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ABSTRACT

Active and Living matter refers to all those systems that consume energy and are not in equilibrium with their surroundings. It is a wide area of research today. Through this report, the pressure applied by active particles on its boundary are studied. Run and Tumble particles are seen to spend more time at the boundary, when a certain amount of active velocity is given to them. The probability to spend time at the boundary increases as the particle's active velocity increases. Inspired by this, Active Brownian particles are used in this experiment and the particle density over a finite time is studied in a fixed circular region for varying active velocities.

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Chapter 1

INTRODUCTION

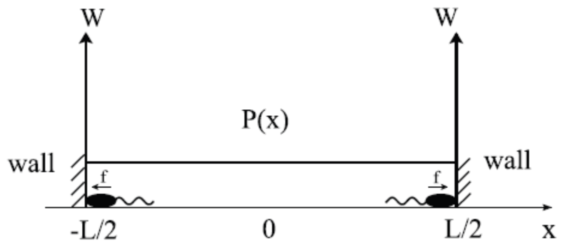
Our cells and tissues form a very complex and dense network. Yet, cancer cells manage to infect a distal site from a localized tumour. Even immune cells travel through crowded environment to reach its target for wound healing. Apart from living systems, self-propelled Janus particles generate flow fields in microfluidic channels. Active stresses play a major role in these phenomena and lead to the directed motion of these systems. This report aims at understanding how active particles exert pressure on boundaries of a confined environment.

1.1 WHAT IS ACTIVE MATTER

Active systems refer to systems which consume energy from external forces and convert them into directed work, existing out of equilibrium. Many living entities like bacteria, cells, tissues are self-propelled and represent active matter systems. Systems like flocks of sheep or birds, movement of cell organelles in the cytoplasm, and even collection of cells show collective behaviour and patterns and are considered as active matter.

1.2 ACCUMULATION OF ACTIVE PARTICLES AT BOUNDARIES

Active particle show a tendency to accumulate at boundaries. This accumulation can arise from numerous factors such as hydrodynamic or surface interactions, as well as due to confinement of the system. If a bunch of Run-and-Tumble swimmers are put in a 1D box with hard walls we can get particle's probability distribution and wall pressure as Fig-1.1. When the length of the box is smaller than the mean free path of some swimmers, the "wave" motion of the swimmers dominant the dynamic behavior. In this scenario, a distinctive bouncing effect occurs: the initial pressure P_0, applied at time t_0, which is the minimum time to reach the boundary starting from the origin with the wall, is higher than the asymptote pressure P_∞. [3]



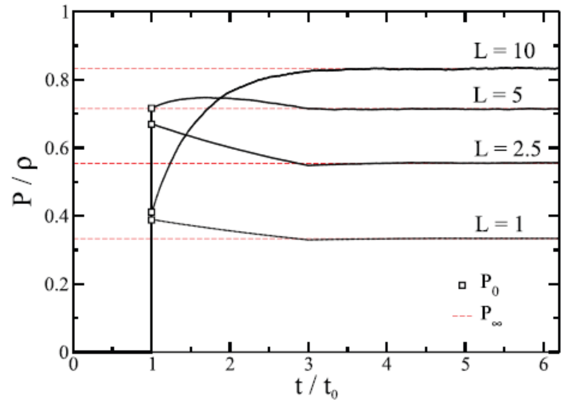


Figure 1.1: (1) Sketch of 1D Run and Tumble Particles with confined walls (2) Plot of Wall Presure(P) with time t/t_0 for different box lengths L. Here t_0 is the minimum time required by the particle to reach the boundary starting from the origin. The square represents the initial wall presuure P_0 at time t_0 and the red line are the Pressure at steady state P_∞

Active fluids have no equation of state in general. Hence pressure is not a state function for active fluids. But it can be one for some fluids that tactically restrict the character of the particle-wall or particle-particle interaction. A system consisting of torque free spherical active Brownian particles is one such example for which an equation of state exists, only when there is no momentum conservation in the bulk.[4]

1.3 DYNAMICS OF ACTIVE SYSTEM UNDER CHANGING SHAPES OF BOUNDARY

Even the shape of the boundary and its changes affect the the dynamics of active fluids and its thermomechanical properties if it is strongly confined within a boundary.[5] In such cases, the distribution of particles at the boundary reaches a steady state directly related to the local curvature of the boundary. With the change in curvature, the pressure exerted on the boundary decreases exponentially relative to the ratio of the curvature radius to the active persistence length.

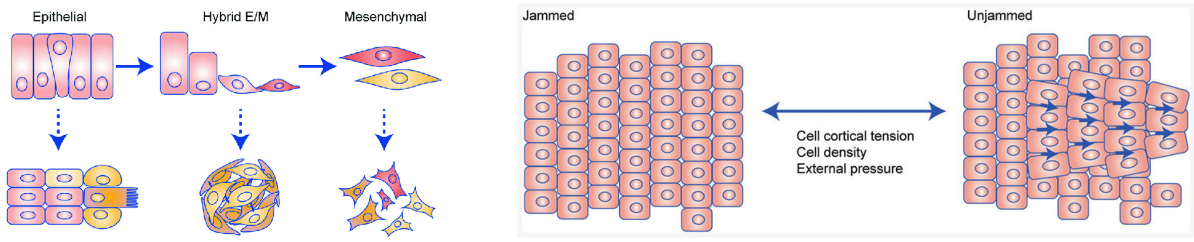


Figure 1.2: (1) This shows epithelial cells losing tight junction during epithelial-to-mesenchymal transition(EMT) which regulates cell migration. (2) Migration being initiated by an alternate route - unjamming transition. Cell clusters can toggle between solid (jammed) and fluid (unjammed) states. Mechanical and geometric shifts in tissue can induce fluidization without the need for EMT-related gene transcription alterations.[1]

This property of active systems help in biological functions such as metastasis of cancer cells, ameboid movement of immune cells or directed migration of epithelial cells or morphogenesis of tissues and organs during embryonic development. Tissue and cell collectives rely on local flow processes, and the transition between jammed and unjammed states, similar to the behavior observed in assemblies of inert particles. For metastasis and cell morphogenesis during embryonic development the jamming-unjamming transition is density driven. But collective behaviour of cells are driven by density independent cell shape driven unjamming transition, which happen due to cell contractility and cell-cell adhesion. Not only individual cells but collectively a cell group also shows shape variability. Cell shape changes are not the only process which cause jamming-unjamming transitions. Various other processes such as cell division, apoptosis, extrusion and motile topological defects may be responsible for this.

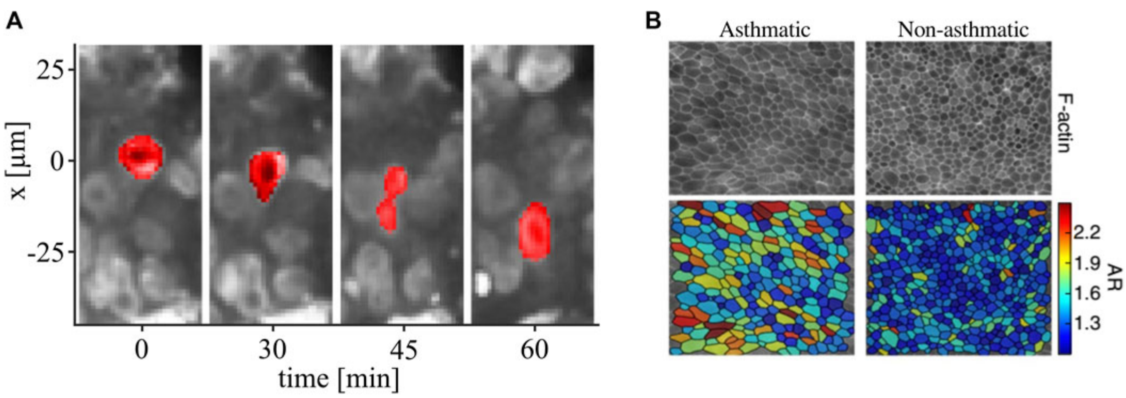


Figure 1.3: Shape-dependent unjamming (A) The change in position of the red spot shows how a cancer cell nucleus moves through a dense 3D cell spheroid with time. (B) This shows that the motility of cell monolayer was more for asthamatic donors than non-asthamatic ones. [2]

Even microorganisms like bacteria and protists show plasticity against external stimuli. Apart from these, non-biological systems such as self-propelled Janus particles can generate flow fields and exert pressure on boundaries of a confined environment of microfluidic channels.

1.4 ENTROPY PRODUCTION OF AN ACTIVE PARTICLE IN A BOX

In contrast to the experiment described in Fig-1.1, where a bunch of Run-and-Tumble Particle (RTP) swimmers where used, here we study motion of a 1D RTP swimmer[6]. These kind of motions are diffusive and long time and length-scales, but when confined to a boundary they show a non-equilibrium steady state distribution. Steady state particle density can be described with the help of an effective potential, whereas non-equilibrium nature can be understood by the entropy generated. The Entropy Production Rate(EPR) is positive when detailed balance is broken in non-equilibrium state. Two Fokker Planck Equations each for two tumble directions- Right and left can be written as:

$$\partial_t R = D\partial_x^2 R - v\partial_x R + \alpha/2(L - R) = -\partial_x J_R + \alpha/2(L - R) \tag{1.1}$$

$$\partial_t L = D\partial_x^2 L + v\partial_x R + \alpha/2(R - L) = -\partial_x J_L + \alpha/2(R - L) \tag{1.2}$$

The probability current density for Left and Right can be given as:

$$J_R(x,t) = vR - D\partial_x R \tag{1.3}$$

$$J_L(x,t) = -vL - D\partial_x L \tag{1.4}$$

The particle spends most of its time in the boundary due to its **persistence**. As the particle is pushed against a wall by its active force, it typically takes twice its persistence time to reverse its direction. If the rate of tumble of the particle is given by $\alpha/2$, then the persistence length of the particle is $\tau = \alpha^{-1}$. Due to this, particle density is more at the boundary, decaying exponentially with the length scale ξ. The relation between ξ and persistence length can be given by :

$$\xi = Pe \times L_p \tag{1.5}$$

where Pe is the Peclet Number defined as $Pe = \frac{v^2\tau}{D}$

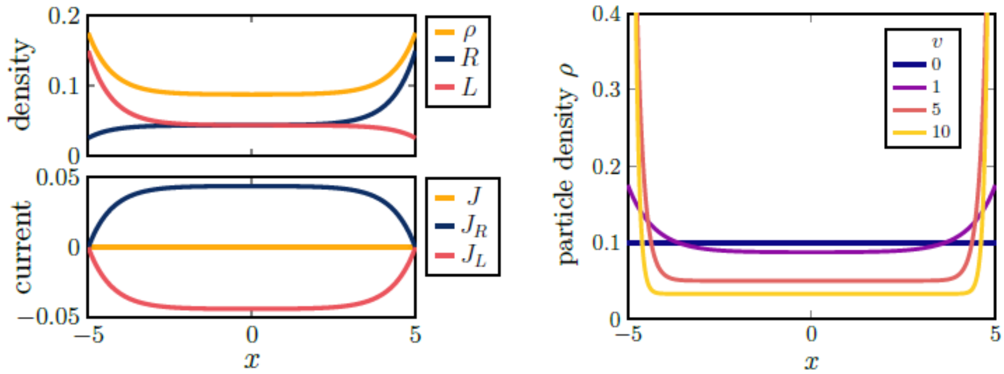


Figure 1.4: (1) Top- This shows the steady state density of the Right(R), Left(L) moving particle and total density ρ. (1) Bottom- This shows the current of Right(J_R) , Left (J_L) moving particles and the total current. The Right moving and left moving current are 0 at boundary and extremizes at centre, satisfying the boundary conditions. (2) This shows the particle density $\rho(x)$ varying with different active velocities v. Clearly with the increasing activity, the RTP particle spends more time at the boundary.

The Rate of Information Entropy can be expressed as sum of two terms-

$$\dot{S} = \pi - \phi \tag{1.6}$$

where π is the Entropy Production Rate(EPR). It is zero for detailed balance and positive when detailed balance is broken. ϕ is the entropy flux from system to environment.

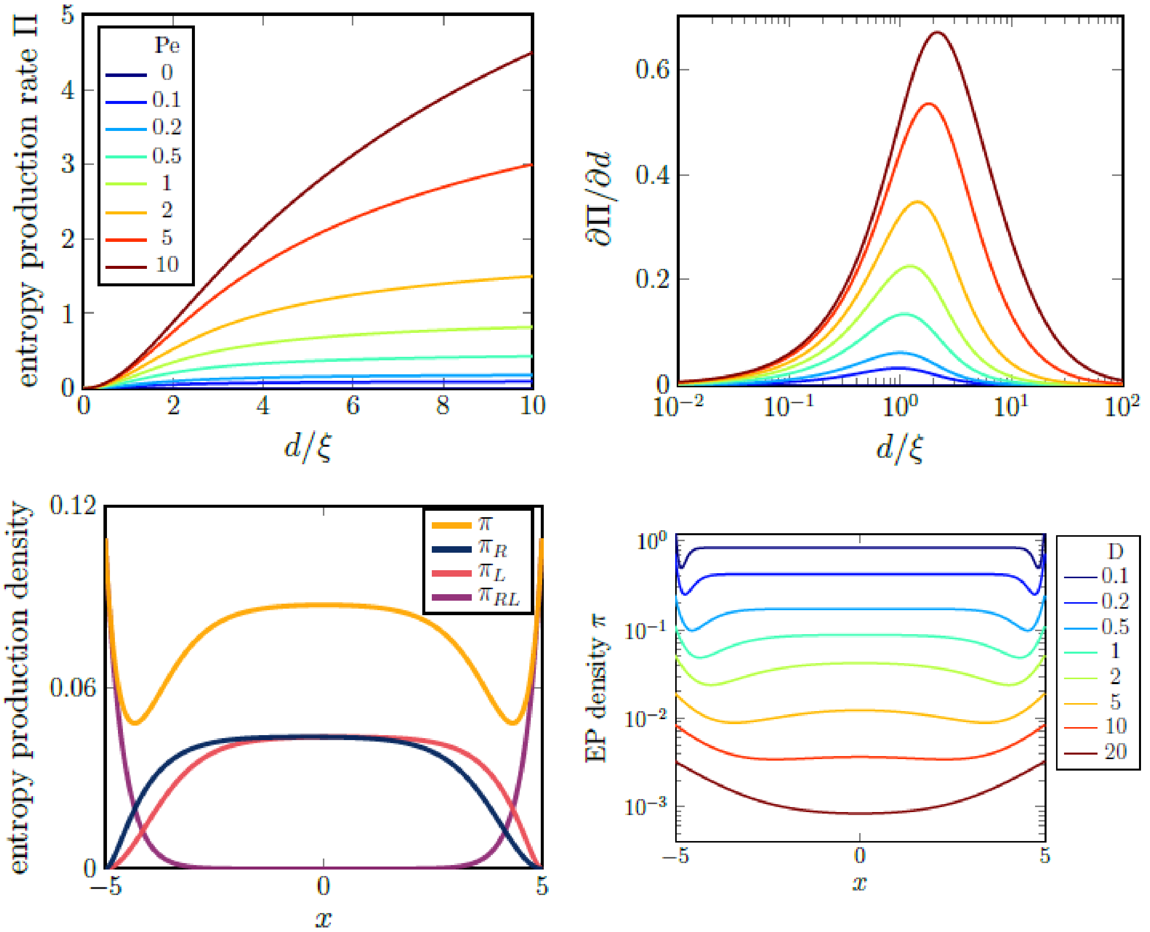


Figure 1.5: (1) π vs $\frac{d}{\xi}$ graph for different Peclet Number (2) $\partial\pi\frac{}{\partial dvs}\mathrm{d}_{\frac{}{\xi}}$ for different Peclet Number (3) Plot of different Entropy Production Rates with distance (4) Plot of π with distance for varying diffusion constant D. The plot shows a change in shape of the EPR function with changing D.

Measuring these quantities is interesting that it might characterise various motility based phase transitions of active systems, especially at criticality.

Studies found that Active Brownian particles can exert stress more efficiently than RTPs due to their property of alignment and generation of stress in a coherent manner.[7] Our aim to visualize the effect of activity on the probability density of an active Brownian particle.

Chapter 2

EXPERIMENTAL SETUP AND IMAGE ANALYSIS

2.1 EXPERIMENTAL SETUP

The setup used to mimic an active system in our lab is shown below

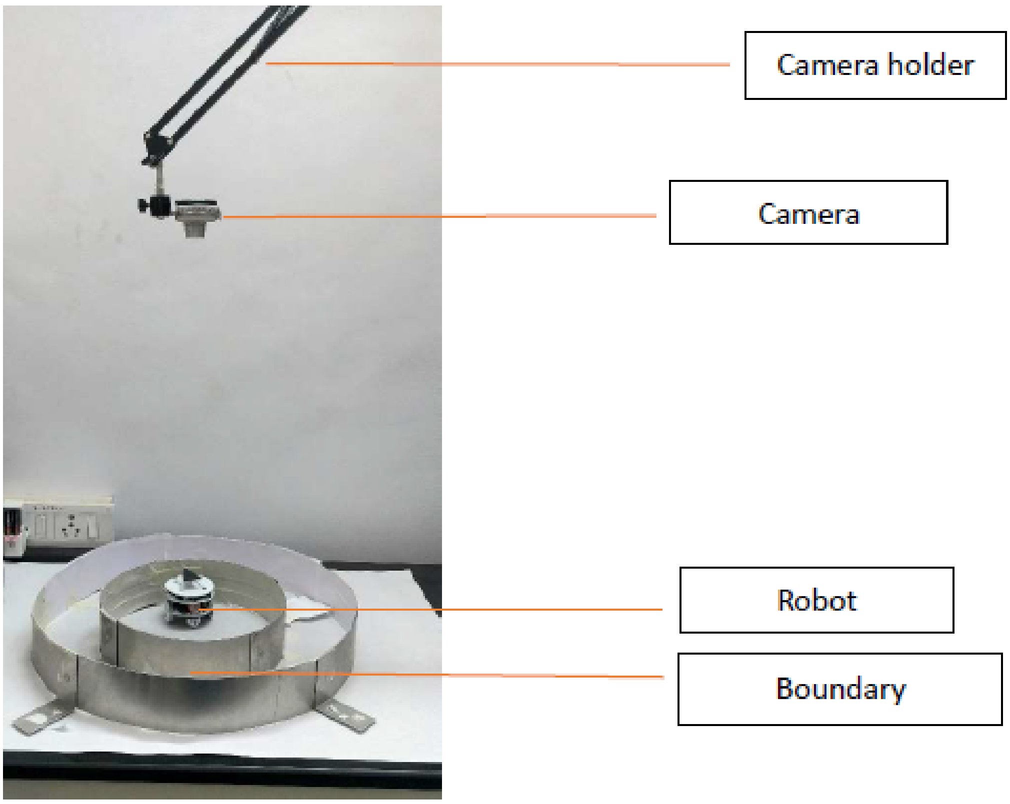


Figure 2.1: Experimental setup

The components of the setup are described herewith

1. Robot : Here the robot is used to perform Active Brownian motion. The components of the robot are

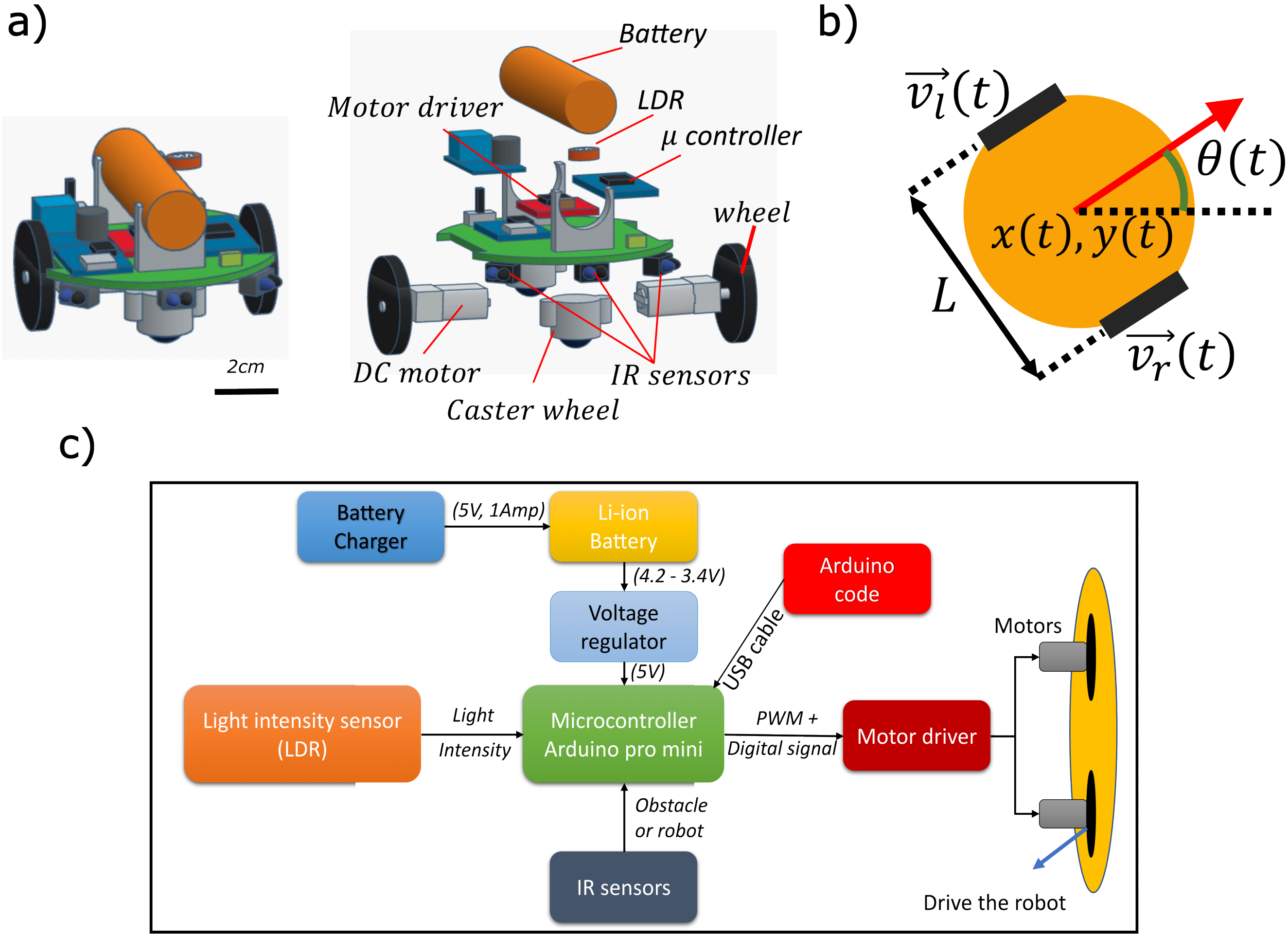


Figure 2.2: Components of the robot

a) Motor driver- This drives the motor.

b) DC DC Booster- This stabilizes the input voltage.

c) Battery- This helps in powering the robot. It is 5Volt chargeable battery.

d) LDR- This helps in sensing any light gradient if used. (This is not used in our experiment.)

e) Micro controller- Here we use Arduino Pro Mini as the microcontroller as the decision making component if the robot. Here we feed the program and the robot performs accordingly.

f) Wheel- These two wheels work independently. Velocity V_l and V_r is provided to each of the wheels, irrespective of each other.

g) Castor wheel- This wheel is used to balance the robot in the forward and backward direction.

h) IR Sensors- This is used to sense the boundaries if appropriate program is input.

i) DC motor- This helps in rotating the wheel.

2. Camera : A digital camera is used with 30 frames per second frame rate.

3. Boundary : The circular boundary is made up of metal. Initially, the larger circle was being used but the smaller boundary was seen to cover the whole statistics. It is covered in white so that it doesnot interfer with the image analysis. The smaller metal boundary create a circular region of diameter 27 cm.

4. Camera holder : The camera holder is stuck to a firm ground so that the camera is stable and it is kept at appropriate height so that the whole field of movement of the robot is covered.

2.2 PROGRAMMING THE ROBOT TO PERFORM ACTIVE BROWNIAN MOTION

To program the robot to perform Active Brownian motion we define two velocity values. One is the width of the velocity range(V) from which we chose the random value of the robot at any instantaneous position. This is also known as the translational noise. And the other is the active velocity (Velocity determined to change the Activity of Brownian particle). Epsilon is the delay time between two given velocity values. The velocity given to the right V_r and the left wheel V_l are different and is given be -

$$V_r = random(-100, 100)/(100.0/V) \tag{2.1}$$

$$V_l = random(-100, 100)/(100.0/V) \tag{2.2}$$

$$V_r = V_r + V_{active} \tag{2.3}$$

$$V_l = V_l + V_{active} \tag{2.4}$$

This can be converted into the analog value as:

$$V_r = (V_r + 0.729)/0.1114 \tag{2.5}$$

$$V_l = (V_l + 0.729)/0.1114 \tag{2.6}$$

2.3 IMAGE ANALYSIS

Image analysis can be done with the help of Imagej software or Matlab. Here, Matlab has been used to extract the position values of the robot.

Figure 2.3: Cropped Image

The orientation value of the robot has also been found out by eroding the image of the robot triangle and then finding the difference in the position values of the two. The formula used is:

$$\theta = \tan^{-1}(\frac{\delta y}{\delta x}) \tag{2.7}$$

$$where \qquad \delta_x = x_{fulltriangle} - x_{erodedtriangle} \qquad and \qquad \delta_y = y_{fulltriangle} - y_{erodedtriangle} \tag{2.8}$$

$$\tag{2.9}$$

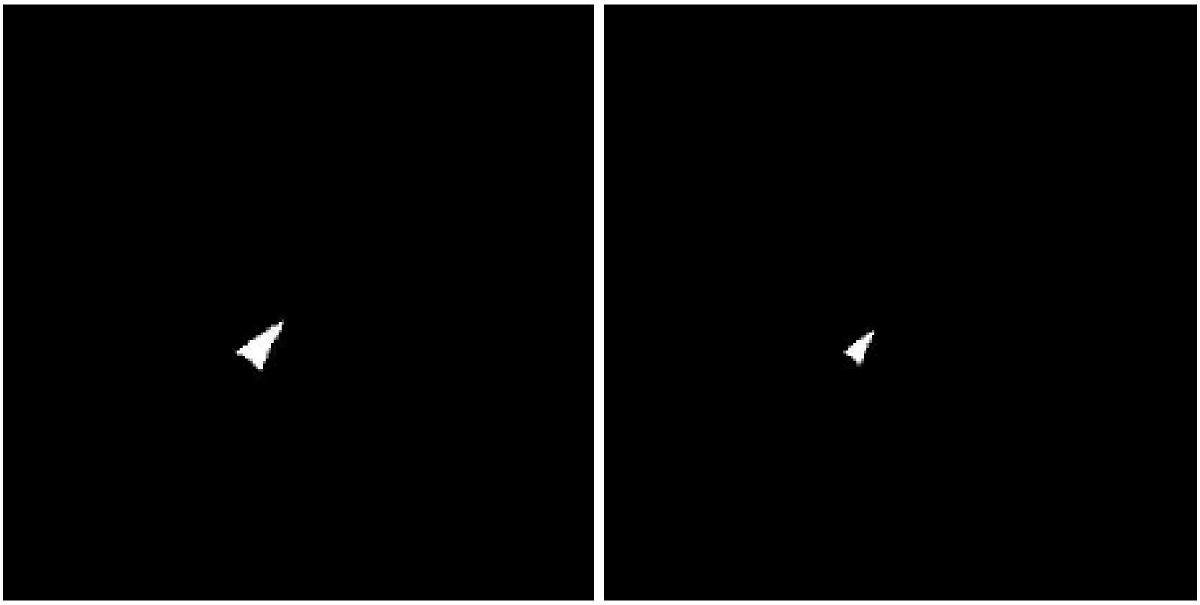


Figure 2.4: Dilated and eroded image of the robot triangle used to determine orientation of the robot at a particular position.

Chapter 3

RESULTS AND DISCUSSION

In our experiment the robot is made to perform Active Brownian motion inside the circular 2D region bounded by the metallic circular boundary. The value of the Translational noise is kept as V=25. The diffusion constant of this motion can be calculated using the formula:

$$D = \frac{\xi V^2}{24} \tag{3.1}$$

where, D= Diffusion Constant

ξ = Delay time between two consecutive velocity values given to the robot=50ms

V = Translational noise

$$D = \frac{50ms \times 25^2}{24} = 1.302 \tag{3.2}$$

1) **Brownian Particle**: V=25 , V_{active}=0

The trajectory of the particle is given as-

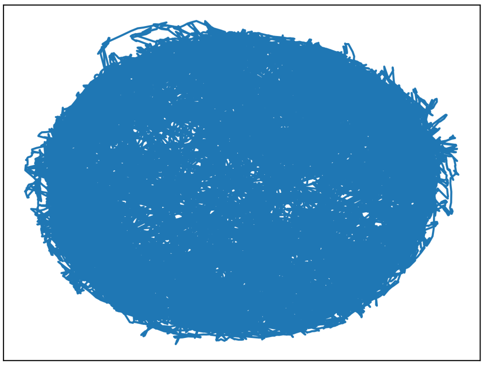


Figure 3.1: Trajectory of the particle for Brownian motion

From this it is clear that the whole circular region is covered by the robot.

The distribution of particle in the circular region:

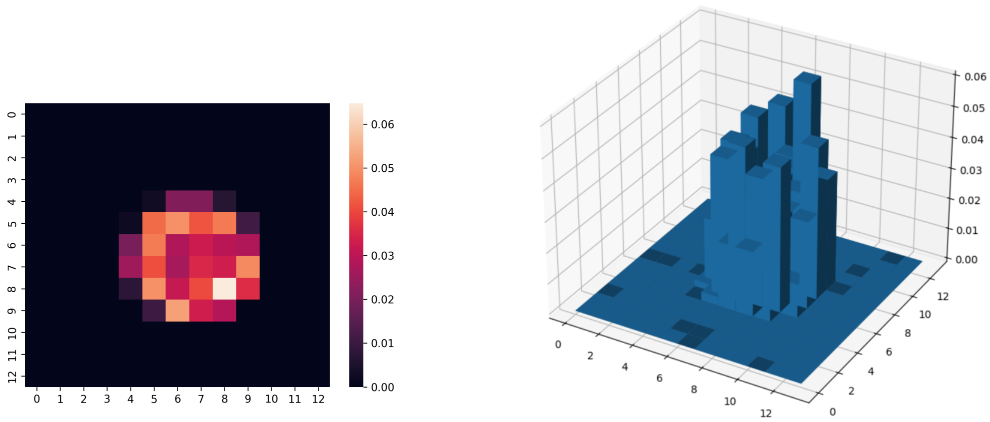


Figure 3.2: (1) Heatmap and (2) 3D plot of the particle density throughout the circular region.

2) **Brownian Particle**: V=25 , V_{active}=1

The trajectory of the particle is given as-

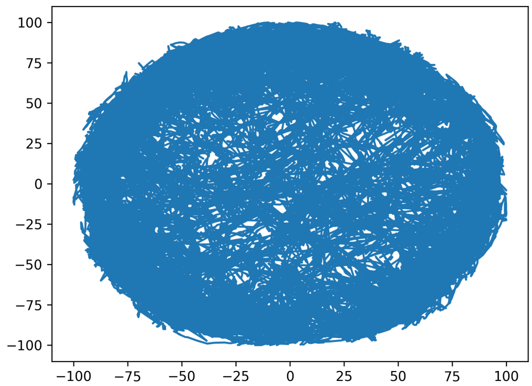


Figure 3.3: Trajectory of the particle for V=25, V_{active}=1

The distribution of particle in the circular region:

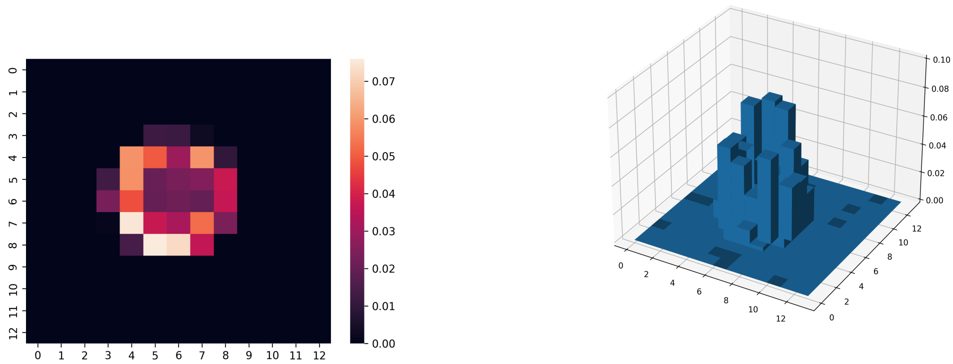


Figure 3.4: (1) Heatmap and (2) 3D plot of the particle density throughout the circular region.

Chapter 4

CONCLUSION

The Brownian particle almost spends a uniform amount of time in the full circular region. It is also seen that the particle spends more time in the boundary than the interior of the circular region for the Active Brownian Motion. This establishes the fact that active particles exerts more pressure at its boundary as the activity of the particle increases. This results in more pressure being applied at the walls of confinement of active particles. If the boundary is flexible, than its shape changes accordingly and we can see various interesting phenomena like jamming-unjamming transitions due to this basic property of active fluids. From here we can also calculate the Entropy Production Rate of the system.

Chapter 5

ACKNOWLEDGEMENT

I want to sincerely thank Prof. Nitin Kumar for guiding me through this project and helping me gain a deeper perception of this topic. I appreciate the meetings and discussions which helped me learn a whole lot of subject matter and also several analysis techniques for realization of this research work.

BIBLIOGRAPHY

[1] Bircan Coban, Cecilia Bergonzini, Annelien JM Zweemer, and Erik HJ Danen. Metastasis: crosstalk between tissue mechanics and tumour cell plasticity. *British journal of cancer*, 124(1):49–57, 2021.

[2] Eliane Blauth, Hans Kubitschke, Pablo Gottheil, Steffen Grosser, and Josef A Käs. Jamming in embryogenesis and cancer progression. *Frontiers in Physics*, 9:666709, 2021.

[3] Luca Angelani. Confined run-and-tumble swimmers in one dimension. *Journal of Physics A: Mathematical and Theoretical*, 50(32):325601, 2017.

[4] Alexandre P Solon, Yaouen Fily, Aparna Baskaran, Mickael E Cates, Yariv Kafri, Mehran Kardar, and Julien Tailleur. Pressure is not a state function for generic active fluids. *Nature physics*, 11(8):673–678, 2015.

[5] Yaouen Fily, Aparna Baskaran, and Michael F Hagan. Dynamics of self-propelled particles under strong confinement. *Soft matter*, 10(30):5609–5617, 2014.

[6] Nitzan Razin. Entropy production of an active particle in a box. *Physical Review E*, 102(3):030103, 2020.

[7] Alexandre P Solon, Michael E Cates, and Julien Tailleur. Active brownian particles and run-and-tumble particles: A comparative study. *The European Physical Journal Special Topics*, 224(7):1231–1262, 2015.