Instituto Tecnológico y de Estudios Superiores de Monterrey

Campus Monterrey

School of Engineering and Sciences

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Induced Rotation of Ratchets in Passive Environments

A thesis presented by

Yeray Cruz Ruiz

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Campus Monterrey School of Engineering and Sciences

The commitee members, hereby, certify that have read the thesis presented by **Yeray Cruz Ruiz** and that it is fully adequate in scope and quality as a partial requirement for the degree of Master in Nanotechnology.

Antonio Ortiz Ambriz, PhD
Thesis Advisor
School of Engineering Sciences, Tecnológico de Monterrey

Someone, PhD
Sinodal member
Affiliation

Someone, PhD
Sinodal member
Affiliation

Someone, PhD
Sinodal member
Affiliation

Dr. Elisa Virginia Vázquez Lepe
Graduate Studiates Director
School of Engineering and Sciences
Monterrey, Nuevo León, México, May 2025

Declaration of Authorship

I, Yeray Cruz Ruiz (student), declare that this thesis titled, "Induced Rotation of Ratchets in Passive Environments" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
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- Where I have consulted the published work of others, this is always clearly stated.
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Yeray Cruz Ruiz (Student)
Monterrey, Nuevo León, México, May 2025

Dedication

For those who come after.

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To my parents for their unwavering support, to my friends for making this journey easier, and especially to Dr. Antonio, who always believed in me and was an incredible mentor.

Induced Rotation of Ratchets in Passive Environments

by

Yeray Cruz Ruiz

Abstract

Swimming at the mesoscale has been a topic of interest for the past two decades because of the complexity of motion at a low Reynolds number, a regime where the viscous forces dominate over the inertial ones. The scallop theorem is a principle that follows these complex ideas and states that a scallop, which has only one degree of freedom, must be unable to have net displacement in this regime due to the lack of time-reversal symmetry of the Navier-Stokes equations. Indifferent to our mathematical understanding, nature was capable of creating biological beings that are able to displace under these circumstances by developing what we call nonreciprocal motion. The esquerichia coli, for example, has a flagellum that rotates in one direction, pushing the fluid backwards and therefore moving the bacteria forwards. Inspired by these ideas, researcher have taken interest in generating motion at those scales. One example are bacterial micromotors, where a dented ratchet is immersed into a bacterial bath where they convert energy from their surroundings into movement. This movement normally follows a ballistic trajectory and in time some of them, will collide into the ratchet transferring their kinetic energy, and therefore making the motor spin thanks to the geometry of the ratchet. Unfortunately, the nutrients they absorb will end and in time the system's medium will need to be replaced, stopping the whole process, therfore being an inneficient process. This is a type of active matter that gets energy from its medium. But, Can we do the same with passive matter?

In this work, we analsze paramagnetic colloids, manipulated by an external precessing magnetic field. The system is confined betwen the z axis and presents periodic boundary conditions in x, and y axis. When multiple particles are present, dipole-dipole interactions arise, leading to either attraction or repulsion depending on their head-to-tail alignment. The particles' internal fields also rotate, dynamically altering their interactions over time. We observe that from 0Hz to 3Hz, the colloids form pairs and start rotating with a shared center of mass, whereas from 3.25 to 7Hz particles have a moment of replsion, creating a neighbor exchange between different pairs, obtaining a ballistic trajectorWe observe that from 0Hz to 3Hz, the colloids form pairs and start rotating with a shared center of mass, whereas from 3.25 to 7Hz particles have a moment of replsion, creating a neighbor exchange between different pairs, obtaining a ballistic trajectory. To investigate whether this motion can perform work, we place a ratchet-like object with different parameters amidst the particles.

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Introduction

Here goes the intro

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Swimming at the mesoscale

2.1 Low Renolds number

At the mesoscale, where objects such as bacteria and colloidal particles operate, the physical world is governed by a regime in which viscous forces dominate over inertial ones. This regime is characterized by a small Reynolds number (Re), a dimensionless quantity that compares inertial to viscous effects. Therefore, the force applied at that moment will describe the movement or displacement performed, not deppending on any past force, this is a characteristic of an overdamped system. In his seminal lecture, Life at Low Reynolds Number, Purcell highlighted the surprising and often counterintuitive behaviors that emerge in such environments [1]. For instance, time-reversible motion — common at macroscopic scales — is ineffective for propulsion at low Re, necessitating non-reciprocal strategies like flagellar rotation or body undulation. This leads to the scallop theorem, that states that an animal with such degrees of freedom — in a viscous regime — will not have a net displacement.

This whole process can be described by the Navier-Stokes equation without the inertia terms, leaving us without any time deppending terms as shown in 2.1.

$$-\nabla p + \eta \nabla^2 \vec{v} = 0 \tag{2.1}$$

This has been a topic of interest for researchers that are constantly looking for ways of transportation in those environments for specific tasks. Unfortunately this is not the only challenge we face when moving at the microscale.

2.2 Brownian Motion and Thermal Noise at the Mesoscale

Even though this is a viscous regime, particles will not be static. At small length scales, such as those of colloidal particles or bacteria, random thermal fluctuations become a dominant source of motion. This phenomenon, known as Brownian motion, was first explained quantitatively by Albert Einstein in 1905. He demonstrated that the irregular paths observed in microscopic particles suspended in fluid result from collisions with the molecules of the surroundings medium [2].

Einstein's work provided one of the first arguments for the molecular nature of matter and led to a mathematical description of how these random movements accumulate over time. Specifically, he derived that the mean squared displacement (MSD) of a particle grows linearly with time:

$$\left\langle x^2(t) \right\rangle = 2Dt, \tag{2.2}$$

where D isthe diffusion coefficient, a measure of how quickly particles spread out. Einstein further related this coefficient to measurable physical parameters through the expression:

$$\mathrm{D} = \frac{k_B T}{6\pi\eta R}. \tag{2.3}$$

Here, k_B is Boltzman constant, T the absolute temperature, η the dynamic viscocity of the fluid, and R the radius of the spherical particle. This rleation — often referred to as the Einstein-Stokes equation — is foundational in soft matter and colloidal physics.

In the systems considered in this thesis, Brownian motion plays a crucial role in the dynamics of passive colloids, and must be accounted for even the presence of external fields or active agents, such as bacteria.

Chapter 3

Name of Appendix

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Chapter 4

Diagnosis in Dynamic Systems

4.1 Definitions

Some important definitions in dynamic systems are:

1. *Static versus dynamic systems.*
   A system is

2. *Linear versus non-linear models.*
   A linear model,

4.2 The Qualitative Model Representation

Bibliography

[1] Edward M Purcell. Life at low reynolds number. In *Physics and our world: reissue of the proceedings of a symposium in honor of Victor F Weisskopf*, pages 47–67. World Scientific, 2014.

[2] Albert Einstein. On the theory of the brownian movement. *Ann. Phys*, 19(4):371–381, 1906.

Curriculum Vitae

Yeray Cruz Ruiz was born in Tlalnepantla, Estado de México, México. He received a Bachelor of Science degree in Mechatronics (2021) from Tecnológico de Monterrey, Campus Monterrey, México, where he is currently a full-time master's student in Nanotechnology, focusing on computational studies of soft matter systems out of thermodynamic equilibrium. His research interests include Soft Matter Physics, Colloidal Models, Spin Systems, Non-Equilibrium Statistical Mechanics, Active Matter, Glassy Systems, and Computational Physics. A passionate advocate for Free and Open Source Software (FOSS), he actively engages in FOSS communities, promoting collaboration and accessibility in scientific research.