THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Contact Modeling and Hardware for In-Hand Perception and Slip-Aware Object Manipulation

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To those that aim for the stars and burn with passion.

Abstract

In-hand perception and object manipulation are key areas that can significantly extend the capabilities of robotic systems. By enabling robots to sense and adapt to their environment, they can perform manipulations with new or unknown objects. Applications range from safely handling delicate items to increasing the workable space of a manipulator and achieving more efficient motions. This thesis advances these capabilities from multiple angles, including the development of new friction models for simulating in-hand slippage, as well as new sensors and parallel gripper hardware for real-world experimentation.

The robotic gripper interacts with objects through the contact surface between its fingers and the object. In this work, we explore and model the friction that occurs at this interface. During planar motion, where both tangential and angular velocities are present, a coupling arises between the tangential and torsional friction forces. We propose planar friction models based on the LuGre model, which captures this coupling using limit surface theory. Two friction models are introduced: a distributed planar friction model that discretizes the contact surface as a baseline, and a faster, numerically efficient model that leverages a pre-computed limit surface.

Slip-aware in-hand manipulation has not yet reached the maturity required for commercialization and readily available hardware. To address this, we designed a custom parallel gripper specifically for fast, closed-loop force control. The gripper is equipped with force-torque sensors and custom relative velocity sensors based on optical mouse technology. This hardware combination enables slip-aware manipulation using only in-hand perception. We demonstrate friction and contact property estimation from an exploration phase, along with four distinct slip-aware controllers. The four slip controllers include trajectory-following for gravity-assisted linear and rotational slippage, hinge control, and slip avoidance.

Keywords: In-hand manipulation, Robot manipulation, Perception, Hardware, Sensors, Contact modelling, Friction modelling.

List of Publications

This thesis is based on the following publications:

[A] **Gabriel Arslan Waltersson**, Yiannis Karayiannidis, “Planar Friction Modelling with LuGre Dynamics and Limit Surfaces”. *Published in IEEE Transactions on Robotics (T-RO)*, vol. 40, no. 10, pp. 3166-3180, 2024.

[B] **Gabriel Arslan Waltersson**, Yiannis Karayiannidis, “Perception, Control and Hardware for In-Hand Slip-Aware Object Manipulation with Parallel Grippers”. *To be submitted.*

Other publications by the author, not included in this thesis, are:

[C] **G.A. Waltersson**, R. Laezza, Y. Karayiannidis, “Planning and Control for Cable-routing with Dual-arm Robot”. ICRA, *International Conference on Robotics and Automation*, Philadelphia, PA, USA, 2022.

[D] R. Laezza, M. Shetab-Bushehri **G.A. Waltersson**, Y. Karayiannidis, “Offline Goal-Conditioned Reinforcement Learning for Shape Control of Deformable Linear Objects”. To be submitted.

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Acronyms

DoF:	Degree of Freedom
CoR:	Center of Rotation
CoP:	Center of Pressure
CoG:	Center of Gravity
F/T:	Force-Torque

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Part I

Overview

CHAPTER 1

Introduction

There is a long-standing dream of creating intelligent robotic systems, robots with the versatility and object manipulation skills of humans. However, replicating these abilities has proven challenging, as what humans do instinctively is the result of eons of evolution. While humans excel in versatility, robots can achieve levels of precision that are unmatched by us. It is as if the world of robotics is upside down—what seems easy for humans is challenging for robots, and what is difficult for humans is simple for machines, as though we have stepped into *Alice's Adventures in Wonderland*. It is important to remember that robots and humans are inherently different, one is mechanical, the other biological. Replicating human-like qualities in machines has been difficult. Mechanical materials may be stronger and tougher, but they wear down over time, whereas humans, though fragile, can heal and adapt. A logical approach might be to continue enhancing the durability of mechanical components, further distinguishing robots from humans. Ultimately, we are left with two worlds, each with its own strengths and weaknesses. Yet, the goal remains the same: to replicate the dexterity and versatility that humans possess.

This thesis aims to contribute to the goal of enhancing the capabilities and versatility of robotic manipulators through slip-aware manipulation. Traditionally, when a robot grasps an object, the object is treated as if it is rigidly attached to the gripper. This approach imposes significant constraints on how the object can be picked up, moved, and placed, as the gripper must match the object's final orientation precisely. In contrast, humans seamlessly adjust their grip on an object based on the scenario, often using only one hand. These subtle adjustments, such as sliding manipulations, happen so instinctively that we rarely notice them. For example, when holding a phone and preparing to place it on a surface, you do not go through a series of rigid, tedious steps, reorienting the phone with both hands. Instead, you perform a near-magical demonstration of dexterity—by intuitively understanding the phone's dynamics and through intricate hand contact, you allow it to slip and reorient smoothly within your grasp, all while minimizing arm movement and conserving energy. Achieving this level of dexterity with traditional robotics would require an inefficient and complex sequence of actions, bearing little resemblance to the human dexterity.

While we are not aiming to fully replicate human capabilities, this thesis seeks to enable simple robotic grippers to perform sliding manipulations. Specifically, we contribute to this objective by extending existing friction models to handle planar motion and arbitrary contact surfaces, allowing for precise simulation of in-hand slippage. Additionally, we design gripper and sensor hardware that enables accurate estimation and slip-aware control.

1.1 In-Hand Object manipulation

In-hand object manipulation refers to the ability to adjust an object's position or orientation relative to the hand or gripper. The implementation of in-hand manipulation varies depending on the gripper hardware employed. For instance, a simple parallel gripper, as shown in Fig. 1.1, which is the focus of this thesis, operates with a single degree of freedom (DoF), and it can only open and close. This limited DoF introduces certain constraints on its manipulation capabilities. In contrast, a human hand, with its 27 DoFs [1], allows for highly flexible and intricate in-hand manipulation. However, it is crucial to recognize that having a higher number of DoFs is not always an advantage. In many industrial applications, reliability is paramount, which often raises concerns regarding complex systems, such as soft robotic or high

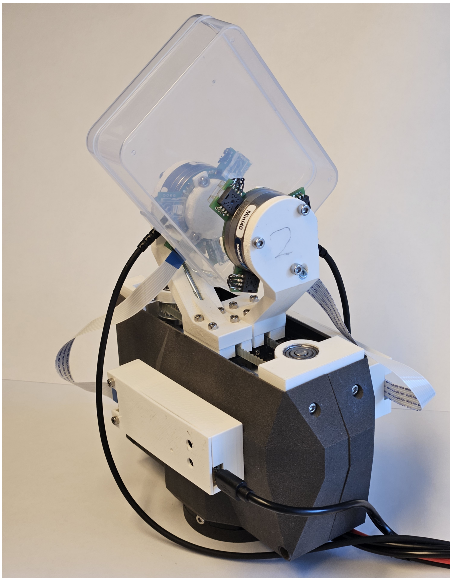

Figure 1.1: *Picture of a custom parallel gripper mounted with force-torque and relative velocity sensors. The gripper is further presented in Paper B.*

DoF grippers [2]. In general, simple mechanical systems tend to be more reliable than their complex counterparts, particularly in industrial settings. While parallel grippers may lack the dexterity of more advanced systems, they compensate with superior grasp strength and simplicity.

This thesis focuses on pushing the boundaries of what can be achieved with parallel grippers, leveraging only a single DoF for control. Despite their simplicity, parallel grippers should not be underestimated in terms of their in-hand manipulation capabilities. With careful design and creative approaches, these capabilities can be significantly extended using extrinsic factors such as gravity, external contacts, or dynamic movements, also referred to as extrinsic dexterity [3]. This thesis focuses on gravity assisted in-hand manipulations, as illustrated in Fig. 1.2.

1. **Linear Slippage:** This involves adjusting the grip force to allow the object to slide down in a controlled manner, repositioning the object relative to the gripper, typically performed with the object center of gravity (CoG) underneath the center of pressure (CoP).

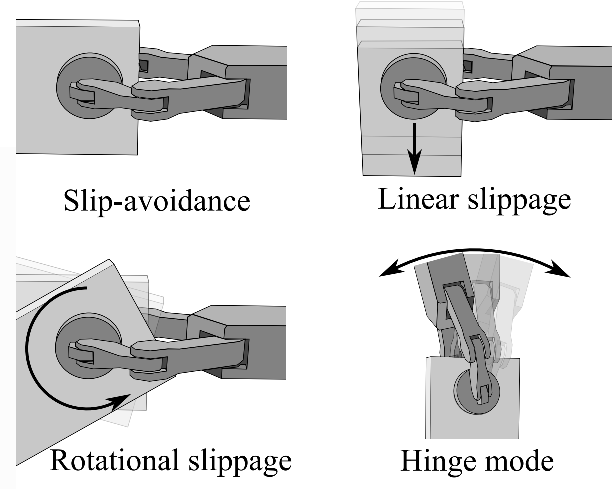

Figure 1.2: *Illustration of three gravity assisted slip modes and one slip-avoidance mode.*

2. **Rotational Slippage:** Here, gravity induces torque on the object, and by adjusting the grasp force, the object can be reoriented within the gripper.

3. **Hinge Mode:** In this mode, the gripper rotates around the object, keeping the object stationary. Typically when the CoG is beneath the CoP.

Furthermore, the slip-avoidance controller is used to prevent slip. The controller dynamically adjust grasp forces to prevent slippage while maintaining the minimal necessary force for stability [4].

While gravity-based slip modes are a primary focus of this thesis, slip-based manipulation can also involve external contact [3]. Figure 1.2 presents examples of such manipulations. External contacts, such as flat surfaces, can facilitate object manipulation through techniques such as pivoting, where the object is reoriented by leveraging a contact point on one of its corners [5]–[10]. During the pivoting action the gripper contact point might slide to accommodate orientation change. Pivoting enables the handling of large objects, which may exceed the robot's direct lifting capability [7], [8]. External surfaces share the load, allowing less powerful robots to manipulate larger

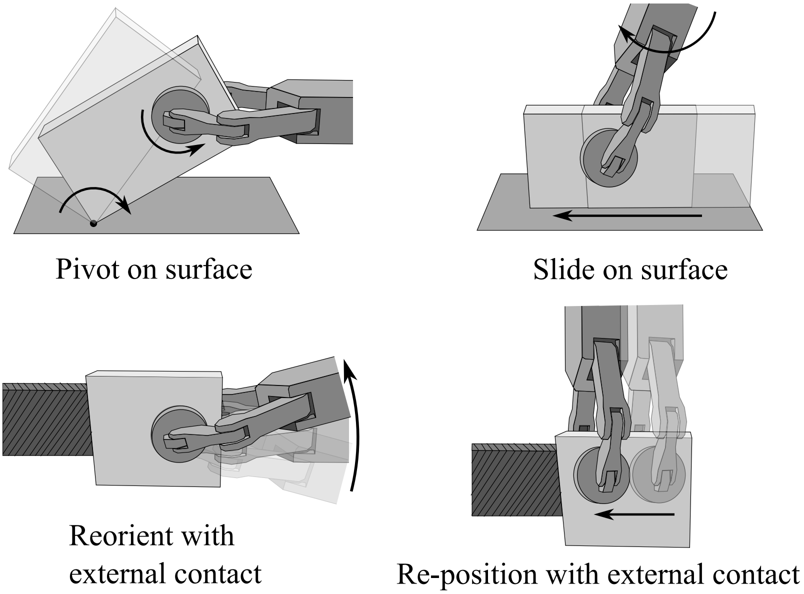

Figure 1.3: *Illustration of slippage control with external contacts.*

objects effectively.

Another common method is sliding, which involves pushing the object across a surface. This technique, explored in various studies [5], [11]–[13], is useful for aligning or packing objects in tight spaces [14]. The pushing of objects on surfaces can be done with combination of in-hand slippage. Additionally, objects can be repositioned in the gripper by pushing them against external contacts which generates a force in the opposite direction of the gripper's motion [15]. The bottom two illustrations in Fig. 1.3 shows reorienting and repositioning objects based on external contacts.

Dynamic control can also be used for in-hand object manipulation, as shown in Fig. 1.4. One approach is dynamic swing-up control, which leverages an object's inertia and momentum to alter its orientation, often against the direction of gravity [16]–[18]. Additionally, objects can be repositioned within the gripper by applying rapid accelerations, a method explored in studies such as [3], [19]. These dynamic manipulation techniques offer the advantage of reorienting or repositioning objects without relying on gravity or external

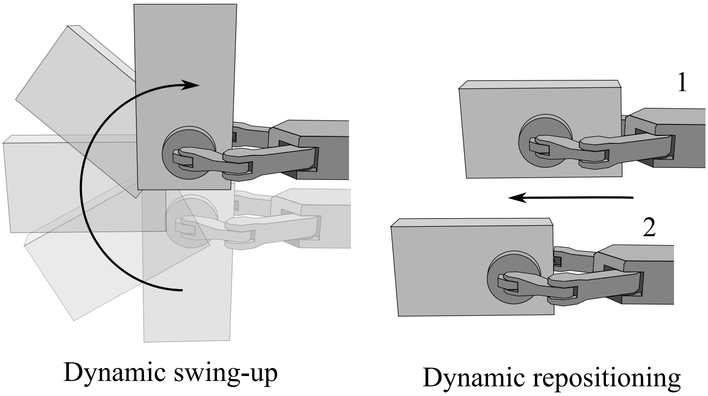

Figure 1.4: *Illustration of dynamic slippage control.*

contacts, though they often require precise control and high accelerations.

One of the primary advantages of in-hand manipulation is its ability to extend the workspace of a robotic manipulator. In typical pick-and-place tasks, the orientation of the gripper significantly affects the robot's reach. As illustrated in Fig. 1.5, the reach is affected by whether the gripper grasps an object from above or the side. Additionally, constraints imposed by the environment during object pickup often limits the robots potential reach, whlile in-hand reorientation could mitigate to problem and reorient the gripper during the task. Slip-aware manipulations can also enhance dual-arm robotic systems by allowing them to adjust their grasp poses [5], [20], [21], illustrated in Fig. 1.5. Rigidly grasping a shared object can heavily limit the system's flexibility. However, by incorporating slip-aware control, the grasp points can be reoriented or repositioned as needed, significantly enhancing the system's overall dexterity and mobility.

All of the above methods rely on the properties of the contact surfaces, whether between the fingers of the gripper and the object, or between the object and external contacts. These contact properties include friction characteristics, pressure distribution across the contact surface, surface curvature, and how the contact surfaces deform. These factors are interdependent; for example, a soft contact pad that deforms to create a larger contact area can generate greater torque than a rigid contact pad with a smaller surface area. Additionally, the size of the contact area influences the coupling between tan-

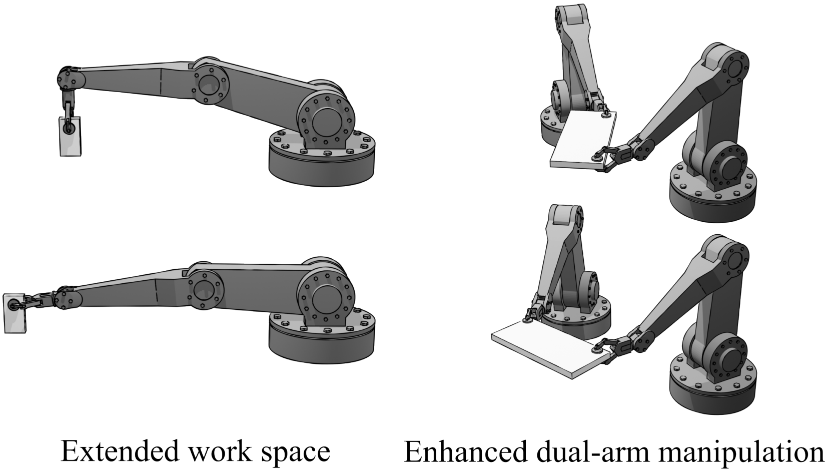

Figure 1.5: *Illustration of slippage control with external contacts.*

gential and torsional friction during planar motion. When an object has angular velocity, it cannot generate the same magnitude of tangential friction force as during pure tangential slippage, which are effects that need to be compensated for. Friction properties dictate the forces that can be exerted and play a crucial role in the transitions between sticking and slipping. Consequently, accurately modeling and simulating these contact interactions is essential for effective in-hand manipulation.

1.2 Contributions

This thesis aims to advance in-hand manipulation capabilities for parallel grippers. The work is presented in two main papers, each addressing different aspects of the problem. Paper A focuses on improving the contact and friction modeling between the gripper and object, specifically simulating friction under planar motions. The key contributions are:

1. We propose a distributed planar fiction model for an arbitrary contact surface and pressure distribution, capable of capturing the stick-slip scenarios. This is achieved by extending the LuGre friction model with the

limit surface theory.

2. To mitigate the computational complexity of the distributed planar friction model, we propose a computational efficient reduced planar friction model. The reduced planar friction model utilizes a pre-computed limit surface and reduces the number of bristles need for simulation to three.

3. The Elasto-Plasic model is extended to planar motions. The LuGre model can experience drifting under oscillating loads, even if they are under the required loads necessary for slippage, the Elasto-Plastic model mitigates the drifting by introducing a elastic part in the model.

Paper B addresses the hardware limitations in the field of in-hand manipulation, focusing on enhancing the capabilities of parallel grippers and sensors. The contributions are:

1. A high performance parallel gripper. For in-hand manipulation, parallel grippers only have control of the grasping force. It is crucial that grasp force can be controlled fast and accurately, commercial gripper has closed architecture for their low level controller and does not offer the capabilities of fast closed-loop force control.

2. Planar velocity sensors. General in-hand manipulation of objects rely on sensing. We propose planar velocity sensors that can be placed ontop of force sensors and accurately measures the sliding velocities. The sensor combination allows us to solely rely on in-hand sensing.

3. In-hand estimation of contact properties. The developed hardware allows for rapid estimation of contact properties at object pick-up.

4. Leveraging the gripper hardware, the sensors and contact estimation we propose four simple slip-aware controllers to demonstrate the capabilities of the hardware. The four slip controllers are trajectory-following for gravity-assisted linear and rotational slippage, hinge control, and slip-avoidance, illustrated in Fig. 1.2.

Together, Papers A and B contribute to advancing the field of in-hand manipulation both theoretically, through improved contact and friction modeling, and technologically, through the design and implementation of specialized hardware.

1.3 Thesis Outline

Part I of this thesis introduces the field and provides the background for the work developed in PartII. The thesis is organized as follows: Chapter 1 introduces the concept of in-hand manipulation, while Chapter 2 covers contact modeling and the interactions between the gripper and object. Chapter 3 provides an overview of tactile sensing and perception. Finally, Chapter 4 summarizes the included papers, and Chapter 5 reflects on the field and discusses future directions.

CHAPTER 2

Contact Modelling

Contact modeling is a critical component of in-hand object manipulation. When a parallel gripper interacts with an object, the interaction occurs through the contact surface between the gripper's fingers and the object, as illustrated in Fig. 2.1. The properties of both the object's surface and the gripper's fingers influence the contact behavior. This chapter focuses on two key concepts: contact pressure distribution and the friction between surfaces.

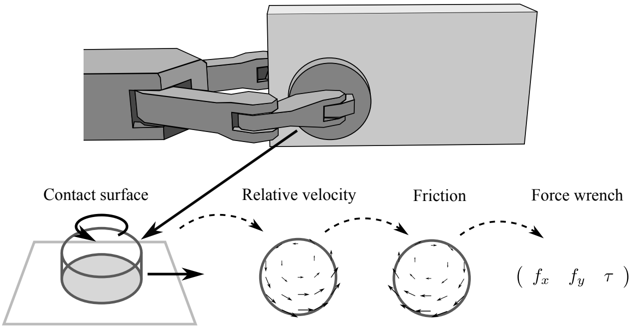

Figure 2.1: *Interaction between the object and gripper under planar motion.*

2.1 1D Friction Models

The modern study of friction dates back to the 18th century with the Coulomb friction model, attributed to Charles-Augustin de Coulomb [22]. The Coulomb friction model describes friction as a force opposite to the direction of motion, proportional to the normal force:

$$f_f \leq \mu_C f_n \tag{2.1}$$

where f_f is the frictional force, f_n is the normal force, and μ_C is the coefficient of friction. The Coulomb friction model is static and does not account for changes in friction with velocity. Despite its limitations, it is precisely because of its simplicity that the model has been widely used in grasping and multi-body simulators. The friction model is often represented as a friction cone [23], where no slipping occurs if the force applied on the surface remains within the cone. When the force reaches the boundary of the cone, incipient slip occurs—a transition state between sticking and slipping, where some parts of the contact surface slip while others remain adhered. Further increases in tangential forces result in full slippage.

In the early 20th century, Stribeck observed that friction depends on the velocity [24]. Initially, when the object is static, friction follows the static friction coefficient μ_S. As the object begins to move, the friction force drops to the Coulomb friction coefficient μ_C. As the velocity further increases, a viscous friction force is observed. This phenomenon is known as the Stribeck effect, as illustrated in Fig. 2.2. Several model variations describe the Stribeck effect [25]; here, we follow [26]::

$$f_f(v) = (\mu_C + (\mu_S - \mu_C)e^{-(v/v_s)^\gamma} + \mu_v v) f_n \tag{2.2}$$

where v is velocity, v_s and γ control the transition between μ_S and μ_C, and μ_v is the viscous friction coefficient. In this model the viscus friction is linearly dependent on the sliding velocity.

Dynamic Friction Models

While the Coulomb and Stribeck models are memoryless, experimental data indicates that friction exhibits dynamic behavior [27]. Dahl introduced a model that accounts for friction dynamics by estimating friction forces from

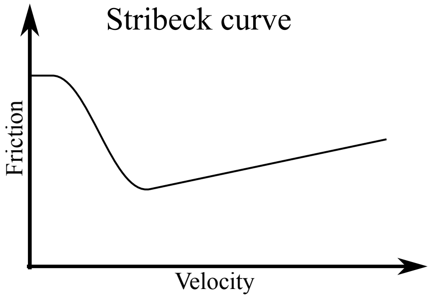

Figure 2.2: Shows the concept of the Stribeck effect, friction is velocity dependent.

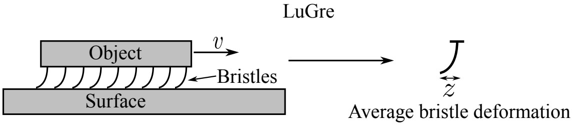

Figure 2.3: Illustrates the bristle deflection analogy of the Dahl and LuGre friction models.

velocity and micro-displacements [28]. In this model, the friction force is represented as bristle deflections modeled by the state variable z:

$$\dot{z} = v - \frac{\sigma_0 |v|}{f_c} z \tag{2.3}$$

where f_c is the Coulomb friction and σ_0 is the stiffness coefficient, and the friction force is given by:

$$f_f = \sigma_0 z. \tag{2.4}$$

The Dahl model does not capture the Stribeck effect. To address this, the LuGre friction model was developed [29], extending Dahl's model to include the Stribeck effect. Like the Dahl model, the LuGre model represents friction through bristle deflection, as shown in Fig. 2.3. In the LuGre model, the bristle deflection z evolves according to:

$$\dot{z} = v - \sigma_0 \frac{|v|}{g(v)} z \tag{2.5}$$

where

$$g(v) = f_c + (f_s - f_c) e^{-|\frac{v}{v_s}|^{\gamma}} \tag{2.6}$$

Here, f_c and f_s represent Coulomb and static friction, respectively. The friction force is then given by:

$$f_f = \sigma_0 z + \sigma_1 \dot{z} + f(v) \tag{2.7}$$

where σ_1 is a damping coefficient and $f(v)$ is viscus friction.

The original LuGre assumes a constant normal force, [30] extended the LuGre model for varying normal loads, often referred to as the amended LuGre model [31]. The amended LuGre model models the bristle deflection for the friction coefficient instead of the force. Similar to (2.5) the bristle deflection is governed by:

$$\dot{z} = v - z\frac{\sigma_0^A |v|}{g^A(v)} \tag{2.8}$$

where $g(v)$ and σ_0 has been replaced with $g^A(v)$ and σ_0^A. The new steady state bristle deflection $g^A(v)$ is given by:

$$g^A(v) = \mu_C + (\mu_S - \mu_C)e^{-|\frac{v}{v_s}|^\gamma}. \tag{2.9}$$

This results in the friction force:

$$f_f = (\sigma_0^A z + \sigma_1^A \dot{z} + \sigma_2^A v) f_n. \tag{2.10}$$

LuGre models capture the stick-slip phenomenon, where objects alternate between sticking and slipping, as detailed in [32]. The effect occurs because the static and Coulomb friction is different. For example, an object laying on a surface that is pulled by a spring would slip when the force induced by the spring equals the static friction force. When the object slips, it transitions to Coulomb friction, which is lower than the static friction force. The net force balance of the object results in a acceleration and when the object is moving faster then the spring is pulled, the force decreases until the object stick again, and the process repeats. In reality, this can occur at a very small scale and at high frequencies.

Elasto-Plastic Friction Model

The Elasto-Plastic model, an extension of the LuGre model, addresses drifting under varying tangential loads, even in sub-slip conditions, as shown in

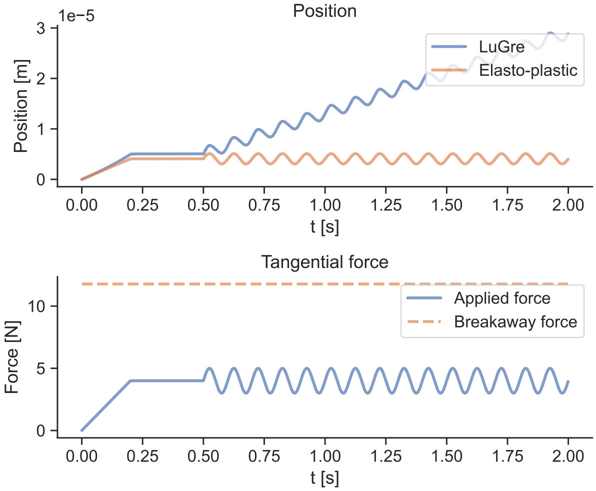

Figure 2.4: *Shows drifting in displacement of the LuGre model when a small oscillating load is applied. It also shows that the Elasto-Plastic model mitigates drifting for the same scenario.*

Fig. 2.4. The Elasto-Plastic model introduces an elastic regime for bristle deflection, preventing drifting. The equation (2.8) that governs the rate of the bristle deflection is modified to:

$$\dot{z} = v - \alpha(z,v) z \frac{\sigma_0 |v|}{G(v)} \tag{2.11}$$

where $\alpha(z,v)$ is a function that govern the elastic versus plastic regimes and is described by:

$$\alpha(z,v) = \begin{cases} 0 & \operatorname{sgn}(v) \neq \operatorname{sgn}(z) \\ \begin{cases} 0 & |z| \leq z_{\text{ba}} \\ \alpha & z_{\text{ba}} \leq |z| \leq z_{\max} \\ 1 & |z| \geq z_{\max} \end{cases} & \operatorname{sgn}(v) = \operatorname{sgn}(z) \end{cases} \tag{2.12}$$

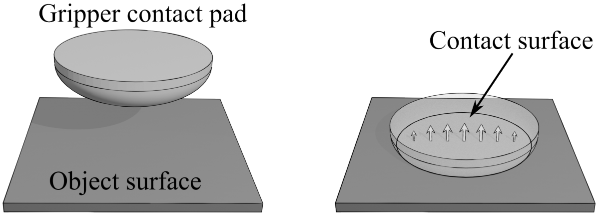

Figure 2.5: *Illustrates the contact surface when a soft contact pad is pressed against a rigid object.*

where z_{ba} is a breakaway threshold. The transition between plastic and elastic is described by:

$$\alpha = \frac{1}{2}\sin\left(\pi\frac{z-(z_{\max}+z_{\mathrm{ba}})/2}{z_{\max}-z_{\mathrm{ba}}}\right)+\frac{1}{2}. \tag{2.13}$$

The elastic behaviour in the sticking regime ensures that the friction force is proportional to the micro-displacement and hence no drifting occurs. The maximum bristle deflection $z_{\max}$ is the steady state deflection $z_{\max} = z_{\mathrm{ss}} = \frac{g^A(v)}{\sigma_0}$. As seen in Fig. 2.4, the Elasto-Plastic model mitigates the drifting under varying tangential loads on an object.

2.2 Contact Surface

When a robotic gripper grasps an object, the contact pad on the robot's finger presses against the object's surface, forming a contact area, as shown in Fig. 2.5. The size and pressure distribution of this contact surface significantly influence the frictional forces and torque generated during planar motion. Larger contact surfaces with pressure concentrated towards the edges can produce more frictional torque than smaller surfaces. Research on soft contact pads, their deformation, and the resulting pressure distributions has been studied in works such as [33]–[39].

The shape and rigidity of the object also play a crucial role in determining the pressure distribution. For instance, a cylindrical object, like a bottle, produces a different contact pressure distribution than a flat surface. In this thesis, we simplify by assuming rigid objects with flat surfaces. However, as Fig. 2.6 shows, mechanical flexing of the gripper's finger pad under load

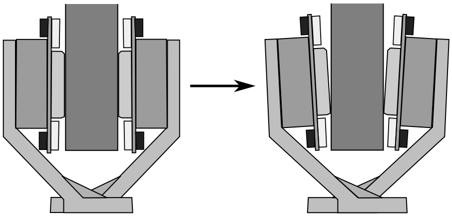

Figure 2.6: *Illustrates that a rigid contact pad and rigid object might not be aligned under high grasping forces due to mechanical flexing.*

affects the contact surface size and distribution, making the contact area force-dependent even for rigid objects and contact pads. For linear slippage, finger flexing has a minor effect, potentially causing small orientation changes as the center of pressure (CoP) shifts. However, during slip-avoidance or rotational slippage, finger flexing directly impacts the amount of torsional friction that can be generated.

2.3 Friction for Surfaces under Planar Velocities

In Section 2.1, we discussed one-dimensional friction, and in Section 2.2, we introduced the concept of contact surfaces. When surfaces exhibit planar motion (both angular and tangential velocities), tangential friction and torsional friction forces are coupled. This relationship can be described by a force wrench, as shown in Fig. 2.1. For example, an object undergoing linear motion requires minimal torque to start spinning. As the object spins faster, torsional friction increases, while tangential friction decreases. The limit surface theory [40], [41] provides a mathematical description of this coupling under Coulomb friction. The tangential forces $[f_x, f_y]^T$ and torque τ are defined by:

$$[f_x, f_y]^T = -\int_A \mu_C \hat{\mathbf{v}}_t(x,y) p(x,y) dA \tag{2.14}$$

and

$$\tau = -\int_A \mu_C [\boldsymbol{\rho}(x,y) \times \hat{\mathbf{v}}_t(x,y)] p(x,y) dA \tag{2.15}$$

where $\boldsymbol{\rho}(x,y) = \begin{bmatrix} x & y \end{bmatrix}^T$ is the position vector with its origin at the CoP, as depicted in Fig. 2.7, and $\hat{\mathbf{v}}_t(x,y)$ is the unit velocity vector at the point

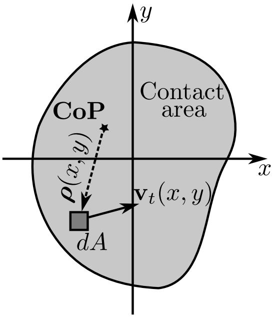

Figure 2.7: *Illustrates contact surface for the limit surface friction model.*

(x, y). The function $p(x, y)$ represents the pressure distribution at that point, illustrated by the arrows in Fig. 2.5.

In Paper A, the expansion of LuGre-type friction models to the planar case is explored. The goal is to develop a friction model that accurately captures slip-stick behavior for planar motions and surfaces, which is essential for in-hand manipulation with robotic grippers. However, the simulations can quickly become computationally complex. To mitigate this, we propose an approximate model that utilizes a pre-computed limit surface and significantly reduces the computational cost.

CHAPTER 3

Tactile Sensors and Perception

Humans possess multi-modal sensory capabilities, enabling the perception of various object properties such as shape, weight, dimensions, surface roughness, humidity, and temperature [23]. These sensory inputs are typically classified into static and dynamic sensing. Dynamic sensing captures changes such as vibrations and tends to respond faster than static sensing, which focuses on the magnitude of a particular stimulus. Numerous review papers discuss tactile sensing, including [42]–[45], but given the extensive number of tactile sensors proposed over the years, this chapter aims to provide an high-level overview of the field.

Tactile sensors specifically refer to sensors that detect local properties of a contact, such as force or temperature. Haptic sensing is a broader term that encompasses tactile sensing as well as other types of perception related to the contact, even those that are indirectly influenced, such as sensing an object's weight based on the effort required to lift it or the shift in balance when carrying it. For example, F/T sensors located in the wrist of a robot can infer information about the contact and are typical examples of haptic sensors. While substantial progress has been made in the development of robotic tactile sensors, widespread industrial adoption has been limited [23].

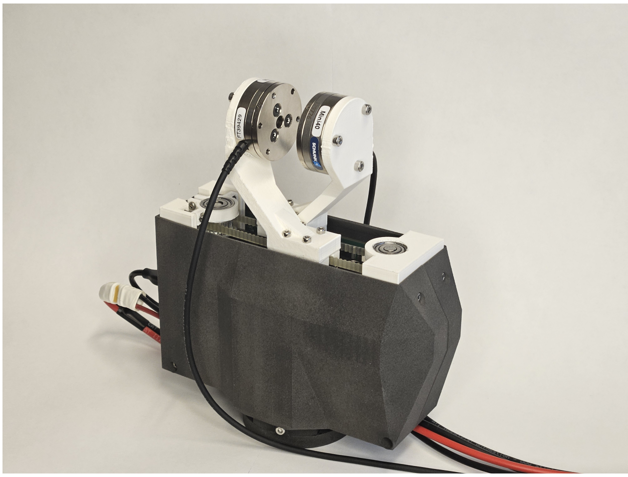

Figure 3.1: *F/T sensors mounted on the fingers of a gripper.*

This is largely because tactile sensors can be challenging to integrate into robust systems, often suffering from issues like drift or non-linear behavior. Ideally, systems should be designed from the ground up with tactile sensing in mind, but this is often impractical in industrial applications. Tactile sensing in robotics is typically divided into several modalities: force, optics, vibration, and temperature.

Force-based tactile sensors measure contact forces, which can range from simple normal force measurements to more complex 6-axis force-torque (F/T) data or even force fields over a surface. The most widely adopted tactile sensing technology in industry is F/T sensors, which are commonly mounted on the fingers of grippers, as shown in Fig. 3.1. F/T sensors have been used for dexterous manipulation tasks in both parallel grippers [46] and multi-fingered robotic hands [47]. These sensors are often combined with friction-based methods for slip-avoidance [23].

Optical-based tactile sensors have gained popularity in recent years, driven by commercialized products like GelSight [48] and easily producible alternatives like TacTip [49]. There are several types of optical tactile sensors [50], but the most prevalent are those that measure surface deformation. These sensors typically consist of a camera and lighting system behind a clear, deformable medium, with a reflective layer at the contact surface. Optical sensors offer the advantage of high-resolution spatial information, which allows for the application of computer vision techniques in tactile sensing.

Slip and object manipulation often generate vibrations, which can be detected by tactile sensors [51]. The BioTac sensor [52], for example, uses a pressure sensor to measure vibrations and can also detect surface temperature. Other vibration-based sensors include those that utilize the vibrations of surface nibs [51], piezoelectric-based slip sensors, and sensors that detect acoustic signals through microphones [23]. However, a common challenge with vibration-based sensors is filtering out non-slip-related vibrations, as these slip induced vibrations are often highly dependent on the material and object being handled.

Tactile sensing is not intended to replace other perception modalities, such as computer vision, but rather to complement them [53]. Each modality has its strengths and weaknesses. For instance, if the goal is to locate an object on a surface, computer vision is the obvious first choice. However, vision does not provide direct information about the object's contact properties. Tactile sensing, on the other hand, can detect when an object is about to slip—something external vision cannot easily capture. Moreover, vision suffers from occlusion issues, and its effective resolution depends on the proximity of the camera. By combining vision and tactile sensing, these two modalities can address each other's weaknesses while leveraging their respective strengths.

The field of tactile sensing remains in its developmental stages, with new sensor technologies being proposed regularly. However, the multi-modal nature of tactile sensing and its dependence on compatible robotic hardware present significant challenges in developing robust and practical solutions for robotics. In Paper B, we design and develop a custom gripper and sensors specifically for in-hand, slip-aware control. The combination of sensors and the gripper's performance distinguishes our work, enabling real-world experimentation without the limitations of commercial hardware and allowing in-hand manipulation with minimal assumptions or reliance on external sensing.

CHAPTER 4

Summary of included papers

This chapter provides a summary of the included papers.

4.1 Paper A

Gabriel Arslan Waltersson, Yiannis Karayiannidis
Planar Friction Modelling with LuGre Dynamics and Limit Surfaces
Published in IEEE Transactions on Robotics (T-RO),
vol. 40, no. 10, pp. 3166-3180, 2024.
DOI: 10.1109/TRO.2024.3410455 .

This paper extends the LuGre friction model to planar motion and arbitrary contact surfaces. First, the contact surface is discretized, and a 2D version of the LuGre model with an Elasto-Plastic extension is proposed. The 2D LuGre model is then integrated over the contact surface to describe the resulting force wrench, which we refer to as the distributed planar LuGre model. While this model provides a detailed representation of the frictional interactions, it is computationally demanding. To address this, we propose the reduced planar LuGre model, which leverages a pre-computed limit surface for the contact area. By reducing the simulated bristle dynamic equations to three, the computational cost is significantly lowered. Both models are tested and compared in various simulated scenarios to evaluate their performance.

4.2 Paper B

Gabriel Arslan Waltersson, Yiannis Karayiannidis
Perception, Control and Hardware for In-Hand Slip-Aware Object Manipulation with Parallel Grippers
To be submitted.

This paper explores the development of custom hardware for in-hand slip-aware control. A custom parallel gripper is designed specifically for closed-loop force control, a feature not typically available in commercial grippers. For perception, we develop custom sensors capable of measuring planar velocity on flat surfaces using optical mouse sensors. These relative velocity sensors are mounted on F/T sensors, which are then placed on the fingers of the gripper, enabling independent measurement of both velocity and force. This setup allows for contact property estimation and we demonstrate four slip-aware controllers, each relying solely on in-hand sensing. The four slip controllers include trajectory-following for gravity-assisted linear and rotational slippage, hinge control, and slip-avoidance. The complete system is mounted on a UR10 robot and undergoes extensive testing to evaluate its performance.

CHAPTER 5

Concluding Remarks and Future Work

This thesis introduces new advancements in contact modeling and hardware for dexterous manipulation using parallel grippers. Chapter 1 provides an overview of in-hand object manipulation, and presents the contribution of the included papers. Chapter 2 delves into contact modeling for flat surfaces, leading into Paper A, which explores friction modeling for planar contact surfaces. Chapter 3 introduces tactile and haptic sensing, setting the stage for Paper B, which presents custom sensors and gripper hardware for novel in-hand manipulation capabilities.

In reflecting on the field, I see untapped potential, though progress has been hindered by the need for multidisciplinary development across both hardware and software. Unlike fields such as computer vision—where solutions like cameras can be developed independently of the final application—tactile sensors must be tightly integrated with gripper hardware, and different sensing modalities in tactile sensing often require vastly different approaches. The absence of commercial components forces researchers to address everything, from custom hardware to control and planning, simultaneously. For me, the challenge of navigating these multiple disciplines is what makes this work both interesting and exciting.

5.1 Future Work

Our work lays the groundwork for future advancements in in-hand manipulation, demonstrating the viability of custom sensors and hardware. While this creates a solid foundation, there remains a significant amount of progress required to turn these concepts into practical, real-world applications.

Immediate future efforts will focus on enhancing the sensing capabilities of the sensor developed in Paper B, with particular attention to improving the contact properties. Beyond that, there are numerous avenues to explore. The new capabilities introduced by these systems will require updates to planning algorithms, which must account for the added capabilities. From a perception and control standpoint, integrating real-time estimation of contact properties holds great potential. One intriguing direction is investigating whether motor current feedback or other forms of haptic feedback could correct drift, a common issue in many tactile sensors.

There is also room to explore additional motion primitives and capabilities, such as dynamic manipulation scenarios like those shown in Fig. 1.4, which could push the boundaries of real-time slip-aware control. In terms of control, refining the trajectory-following slip controllers for smoother, more reliable performance is essential.

Finally, the fusion of tactile sensing with computer vision remains largely untapped. Rather than replacing vision, tactile sensors should be seen as complementary technologies. By combining their strengths, the field could move closer to achieving robust and reliable perception systems for in-hand manipulation.

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