## Title

Adaptive Visuotactile-Guided Control for Dexterous In-Hand Rolling of Slender Objects

## Abstract

### V1

Current robotics faces a dilemma in manipulating slender objects, forcing a choice between two insufficient paradigms. Specialized systems provide the critical sub-millimeter precision for delicate procedures, but are functionally rigid, creating bottlenecks and increasing procedural complexity in dynamic workflows that require switching between instruments like guidewires and catheters. Conversely, general-purpose grippers, while adaptable, lack the delicate force control and stable contact mechanics required for such fine-scale tasks. Consequently, a crucial class of dexterous, multi-stage manipulations remains beyond the reach of automation, caught between the limits of inflexible precision and unstable versatility.

We bridge this gap with an Adaptive Visuotactile-Guided Control framework. Our system leverages a multi-DoF, sensorized gripper to perform force-position coupled in-hand rolling, adaptively handling objects from sub-millimeter wires to 5mm catheters with a single end-effector. Experiments validate that our approach successfully balances this trade-off, achieving application-sufficient precision while providing the versatility needed to automate complex, multi-instrument tasks.

### V2

The robotic manipulation of slender objects is fundamentally limited by a trade-off between precision and versatility. Specialized grippers provide sub-millimeter accuracy but are rigid by design, failing in dynamic, multi-object workflows. Conversely, general-purpose grippers offer adaptability but lack stable contact and fine force control which is essential for delicate tasks. This leaves a critical class of dexterous, multi-stage manipulations beyond the reach of automation.

We resolve this dilemma with an Adaptive Visuotactile-Guided Control framework. Our system features a multi-DoF, sensorized gripper that performs force-position coupled in-hand rolling. It robustly manipulates a continuous range of slender objects, from sub-millimeter fibers to 5mm rods, with a single end-effector. Experimental results demonstrate that our approach successfully combines precision and versatility, enabling the automation of complex, multi-object manipulation tasks.

## Introduction

### Outline

*The Grand Challenge (Paragraph 1): Start with your broad problem statement.*

*The Specific Dilemma (Paragraph 2): Introduce the core "precision vs. versatility" trade-off.*

*Requirements & The Gap (Paragraph 3): .*

*Solution and Contributions (Final Paragraph):*

### V1

Dexterous manipulation of slender objects—like fine wires, optical fibers, or surgical sutures—poses a grand challenge in robotics. Mastering this class of objects is a critical step toward the next generation of automation in high-stakes domains, from microsurgery to the assembly of intricate electronics. Unlike rigid bodies, the dynamics of slender objects are complex and unpredictable, demanding a level of finesse that lies at the frontier of modern robotic perception and control. Achieving human-like dexterity in these tasks promises to unlock new surgical procedures, accelerate scientific discovery, and create truly adaptable manufacturing lines.

Yet, current robotic systems present a stark trade-off between precision and versatility. On one hand, specialized mechanisms can achieve sub-millimeter accuracy for a single, well-defined task. However, these systems are inherently brittle, often failing at the slightest deviation from their programmed function. On the other hand, general-purpose grippers offer adaptability but typically lack the stable contact and delicate force control needed for fine-scale work. They treat a fragile fiber like a blunt instrument, leading to unstable grasps and rendering them clumsy and unsafe for procedures where dexterity is paramount.

To bridge this gap, an ideal system must unite three capabilities that are currently separate. First, it requires stable, continuous contact to execute controlled motions like rolling without slippage. Second, it needs high-resolution tactile feedback to perceive and regulate minute interaction forces, preventing damage to the delicate object or its surroundings. Third, it must possess intrinsic in-hand dexterity to adapt to various object sizes and perform complex motions on the fly. The effective integration of these three capabilities remains an open and critical research gap.

To fill this gap, we present an Adaptive Visuotactile-Guided Control framework. Our approach uses a novel multi-DOF gripper with visuotactile sensors to gain fine-grained control over an object's in-hand pose while regulating interaction forces. This tight coupling of rotational displacement and applied force is the key to dexterous in-hand rolling. In this paper, we make three primary contributions:

1. A novel, dual-DOF dexterous fingertip mechanism, integrated into a parallel gripper and designed specifically for in-hand rolling.
2. A coupled force-pose control algorithm that leverages visuotactile feedback for robust manipulation of sub-millimeter objects.
3. Experimental validation on a simulated surgical platform, demonstrating the system's effectiveness in a complex, multi-object task.

## Related Work

**2.1 Dexterous Fingertip Manipulation: Discuss prior research on robotic finger/gripper design for fine manipulation. What have others done? What are their limitations**

**2.2 Visuotactile Sensing for Control: Survey the different types of visuotactile sensors (like GelSight, TacTip, etc.) and how they have been used in control loops. What information can they provide? What challenges remain in using them for this specific task?**

**2.3 Robotic Systems for Interventional Surgery: Review existing surgical robot platforms (like the Da Vinci, or more specific catheter-guidance systems). Highlight their limitations, which will reinforce the "dilemma" you introduced earlier**

*(Figure 1: System Overview)*

## Methodology / Theory

### Coupled Force-Position Relationship in Fingertip Manipulation under Compliant Rolling Contact

Before detailing our model, it is important to frame its contribution in a practical context. The operation of slender, flexible objects often relies on an operator's intuition, guided by visual feedback from the object's distal tip. Due to the object's compliance, rotational manipulation applied locally by a gripper does not necessarily translate directly to the pose of this tip.

Our work, therefore, does not attempt to model the complex dynamics of the entire flexible body. Instead, we focus on a foundational prerequisite: ensuring the robustness and consistency of the manipulation action itself. The goal of our control algorithm is to precisely model and control the local rotational displacement at the point of contact. By doing so, we provide a predictable and repeatable "building block" for manipulation. The broader challenge of modeling how this local rotation affects the final tip pose is considered beyond the scope of this paper.

Regime 1: Kinematic Rolling of Thicker Objects (d≥2 mm)

For objects with a diameter of 2 mm or greater, the gripper fingers maintain a separation gap even after a secure grasp is established. In this configuration, we can model the system as the non-slip rolling of a rod between two parallel racks, similar to a rack-and-pinion mechanism.

The theoretical rotational displacement is derived from the linear travel of the fingertips. Given a linear travel per motor step, s, the total effective displacement generated by the two opposing fingers for n steps is 2sn. The ideal angular displacement in degrees is thus:

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However, this ideal model must be corrected for two real-world factors. First, any angular misalignment, ϕ, between the gripper and the object's axis means that only the perpendicular component of the finger motion contributes to the rotational torque. This is accounted for by a cos(ϕ) term. Second, to compensate for unmodeled effects such as material compliance and mechanical friction, we introduce an empirically determined correction factor, K rod.

This leads to the final model for this regime:

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Regime 2: Deformation-Based Rolling of Thinner Objects (d≤1 mm)

When manipulating sub-millimeter objects, the dynamic model changes significantly. The gripper fingers close completely, making contact with each other and enclosing the slender object within their soft, deformable pads. The physics of this state are far more complex, dominated by material compression and frictional forces.

To create a tractable model, we narrow the scope to a non-slip scenario for a limited range of motion (n≤30 steps). In this case, we observed experimentally that the object's rotation is primarily caused by the shearing deformation of the soft finger material, rather than kinematic rolling. Our data revealed a strong linear relationship between the number of motor steps and the resulting rotation, with the object's specific diameter having a statistically insignificant effect.

This relationship is captured by the following linear model:

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where m wire is the empirically derived gain (deg/step) and C wire is a constant offset that accounts for system backlash or initial material slack.

Unified Rotational Pose Model

Combining these two models yields the final piecewise formulation for our pose control algorithm:

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where the constants are empirically determined as {check formulation}. This hybrid model allows our controller to adapt its strategy based on the object being manipulated, forming the foundation of our system's versatility.

### Simulation of Rotational Twisting and Rolling

*(Figure 2: Simulation Results)*

### A Safe Coordinated Manipulation Strategy for Catheters and Guidewires with a Single Gripper

## Robot System Design

*(Figure 3: System Architecture)*

**Overall Structure of the Visuotactile-Based Mechanical Gripper**

## Experiments

**Calibration of Visuotactile-Based Catheter/Guidewire Manipulation**

*(Figure 4: Experiment 1 Setup and Results)*

**Calibration of Visuotactile-Based Force Sensing for Manipulation**

*(Figure 5: Experiment 2 Setup and Results)*

**Teleoperated Coordinated Manipulation of Catheter and Guidewire using a Single Gripper** *(Figure 6: Experiment 3 Setup and Results)*

## Discussion

## Conclusion