## Title

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

## Abstract

## Introduction

The stable and versatile manipulation of ultra-fine objects—such as fine needles, guidewires, optical fibers, and microelectrodes—remains a critical challenge in the field of embodied artificial intelligence. This is particularly true in complex and demanding scenarios like minimally invasive medical surgery and flexible industrial assembly. Robots equipped with the ability to manipulate these objects with human-like dexterity offer distinct advantages:

1. Unlike standard, anthropomorphic hands can rapidly switch between different ultra-fine objects at a low cost.
2. This manipulation method enables high-degree-of-freedom spatial adjustments without the need for additional tools.

However, due to the minute scale of these objects, their mechanical responses and frictional contact characteristics differ significantly from those of conventional objects, making precise control extremely challenging.

## Related Work

**Visuotactile Sensors**

**Fingertip Manipulation Techniques**

**Vascular Interventional Surgery Robots**

**Three Key Requirements for Interventional Surgery Robots**

* Requirement 1: Coupled Force-Position Control at the Fingertip
* Requirement 2: Coordinated Manipulation and Switching of Catheters and Guidewires

**The Three Main Contributions of This Paper:**

* Contribution 1: Design of a two-degree-of-freedom fingertip twisting and rolling mechanism deployable on a robotic arm.
* Contribution 2: Proposal of a bio-inspired, visuotactile sensor-based force-position control algorithm for the manipulation of ultra-fine (sub-millimeter) catheters and guidewires.
* Contribution 3: Development and experimental evaluation of a simulated vascular interventional surgery platform based on the proposed system.

*(Figure 1: System Overview)*

## Methodology / Theory

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

**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**

**Master-Slave Teleoperation Robot System**

## 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