ABSTRACT

Nanorobotic manipulation inside electron microscopes is a specialised technique for handling nanomaterials in nanofabrication and multiphysical properties characterisation; however, it faces significant constraints. The challenges arise from limited perceptual abilities, the need for accurate sensing of nanoscale interaction forces, restricted workspace geometry, and the requirement for precise human–machine coordination. These limitations directly affect the accuracy, robustness, repeatability, and reliability of any robot-assisted manipulation tasks performed at the micro- and nanoscales. This thesis addresses these challenges by designing and developing a comprehensive *in situ* nanorobotic manipulation framework that integrates bilateral teleoperation, physically informed force modelling, visuo-haptic feedback, multiscale control, and path-planning support.

A key contribution of this work is the development of a haptic feedback-assisted master–follower scaled bilateral teleoperation system capable of rendering nanoscale interaction forces to the human operator in real time. The proposed framework integrates a simulation environment with analytically modelled nanoscale contact mechanics and the experimental setup, enabling direct, virtual, or augmented mode control. Unlike conventional microscope-based systems that rely primarily on visual supervision, the developed visuo-haptic interface introduces bidirectional sensory integration, enabling simultaneous perception of force and visual signals during manipulation. Experimental validation is carried out through simulated and real-time manipulation scenarios, and system performance is evaluated based on trajectory-tracking accuracy and force-feedback fidelity. Another significant contribution is the incorporation of vision-based feature extraction to digitally twin the nanoscale working task space and generate feasible manipulation paths, reducing operator workload and improving repeatability. This work contributes toward more reliable and scalable human-in-the-loop nanorobotic systems for advanced micro- and nanoscale applications.

Furthermore, this thesis advances the state of the art by introducing cooperative path-planning strategies for multi-micromanipulator coordination within the highly confined workspace of an electron microscope for manipulation and assembly tasks. By integrating environment modelling with optimal path generation, the proposed framework ensures collision avoidance, task feasibility, and smooth transitions between free-space motion and contact-driven manipulation. The established novel 3D nanomanipulation techniques allow handling and assembly of multidimensional nanomaterials, and the incorporation of path-planning modules automates key steps. In addition, an innovative web-based supervisory application interface has been developed to incorporate these modules and provide access to system control, visualisation, and task execution, enabling intuitive interaction with the nanorobotic system through real-time visual feedback and high-level command inputs.

***Keywords*:** Haptics, Nanorobotic Manipulation, Path planning, SEM.