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Title of Article

Nano-Scale Piezoelectric Actuation for In-Vivo Robotic Navigation Across Vascular Microchannels

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Abstract

Navigating in-vivo robotic systems across sub-capillary vascular microchannels demands actuation modalities that are mechanically efficient, bio-compatible, and dynamically controllable within confined fluidic geometries. This study introduces a nano-scale piezoelectric actuation framework leveraging flexural lead zirconate titanate (PZT) fins and barium titanate ($BaTiO_3$)-based spiral propulsors to achieve pulsatile locomotion in highly viscous blood-mimetic environments. The actuation system is integrated into a soft robotic capsule, featuring phased electric signal routing and real-time trajectory correction using edge-aware capacitive sensors. In-vitro experiments with synthetic vascular phantoms, coupled with ex-vivo microchannel scaffolds, demonstrate controllable navigation through bifurcating channels, with actuation efficiencies exceeding 68% under laminar flow and high localization stability across dynamic flow gradients. Cytocompatibility assays confirm minimal hemolysis and endothelial disruption, while thermal mapping reveals sub-physiological dissipation levels. The platform sets the foundation for intelligent, minimally invasive robotic agents capable of deep vascular access, targeted drug delivery, and microscale tissue interrogation.

Keywords

Piezoelectric actuation · Nano-robotics · In-vivo navigation · Vascular microchannels · Soft robotics · Cytocompatibility · Biofluid dynamics · Signal gating · Micropropulsion · PZT actuators

Introduction

The pursuit of autonomous in-vivo navigation through sub-capillary vascular networks has catalyzed innovations at the intersection of nano-electromechanics, biomedical robotics, and piezoelectric material science. At the heart of this endeavor is the challenge of actuating bio-compatible micro-scale robotic systems within tortuous, fluid-filled environments—where conventional electromagnetic or thermal propulsion modes prove ineffective or biologically disruptive.

Piezoelectric actuators, particularly those engineered at the nano scale from materials such as lead zirconate titanate (PZT), barium titanate ($BaTiO_3$), and 2D ferroelectric composites, offer high-force density, electro-mechanical coupling, and directional controllability within confined geometries. When structured into flexural micro-fin arrays, cantilever walkers, or spiral propulsors, these actuators can generate localized pulsatile motion and steerable thrust even under hemorheological constraints.

This study presents a modular navigation framework for robotic capsules embedded with nano-piezoelectric actuation systems, optimized for microvascular traversal. Emphasis is placed on:

- Characterizing actuation efficiency under laminar and pulsatile flow regimes.
- Benchmarking trajectory control against channel bifurcations, branching angles, and boundary adherence.

- Evaluating biofluid compatibility, cytocompatibility, and thermal dissipation profiles across synthetic and ex-vivo vascular scaffolds.

The design integrates soft robotic principles with topology-aware control circuits and phased piezo signal routing. The robotic construct is guided via real-time feedback from onboard vibration sensors and capacitive edge-tracking systems—forming a closed-loop navigation system that adapts to structural variations in the vascular environment.

Methods

Actuator Fabrication and Nano-Structural Integration

Piezoelectric actuators were fabricated using sol-gel deposition of lead zirconate titanate (PZT) and sputter-assembled barium titanate ($BaTiO_3$) thin films onto silicon-nitride cantilever substrates. Flexural fin arrays (40–150 μm in length) and spiral walkers (~100 μm radius) were micro-patterned via focused ion beam etching to produce directional propulsion profiles. For bio-integration, surfaces were functionalized with PEG-silane linkers to minimize thrombogenic adhesion and ensure hemocompatibility.

Soft Robotic Capsule Assembly and Signal Gating

The actuator array was embedded in a soft elastomeric capsule (~300 μm diameter) composed of PDMS and ecoflex composites, encapsulating onboard capacitive sensors and piezo drive circuitry. Signal gating was achieved using phased activation pulses (2–10 V peak-to-peak, 1–100 Hz), modulated by edge-aware feedback from capacitive filaments that track proximity to vascular walls. This closed-loop actuation enabled real-time steering, propulsion modulation, and obstacle avoidance across bifurcating channels.

Vascular Phantom Fabrication and Microchannel Simulation

Synthetic vascular networks were printed using two-photon polymerization of hydrogel-based bioinks, forming microchannels with diameters ranging from 60–200 μm and branching angles of 15°–90°. Flow profiles were simulated via peristaltic micropumps, reproducing laminar and pulsatile regimes consistent with physiological microvascular flows (0.1–1.2 mm/s). Pressure sensors and particle imaging velocimetry (PIV) were employed to monitor flow dynamics and assess robotic interaction within varying channel geometries.

Trajectory Monitoring and Actuation Efficiency Benchmarking

Locomotion trajectories were monitored via high-speed microscopy and infrared imaging across synthetic and ex-vivo microchannel scaffolds. Actuation efficiency was quantified by displacement per actuation cycle, normalized to flow resistance and capsule drag coefficient. Navigation stability was assessed through repeated traversal of bifurcating channels with variable curvature and hemodynamic shear.

Cytocompatibility and Thermal Dissipation Analysis

To evaluate biological safety, capsules were incubated with human endothelial cells (HUVECs), erythrocyte suspensions, and platelets. Hemolysis assays, nitric oxide expression levels, and tight junction integrity were measured post-actuation exposure. Thermal dissipation during prolonged activation cycles was tracked using micro-thermistors embedded within the capsule, ensuring that surface temperatures remained below 37°C throughout operation.

Results and Discussion

Actuation Dynamics and Trajectory Control

Nano-scale piezoelectric actuators exhibited pulsatile displacement profiles consistent with flexural resonance modes, producing net forward locomotion of robotic capsules across channels as narrow as 80 µm. Under laminar flow (0.5 mm/s), flexural fins achieved 6.2 µm displacement per cycle, translating to sustained navigation rates of 0.8 mm/min. Spiral actuators demonstrated superior rotational steering, enabling capsule redirection at bifurcating junctions with turning radii below 120 µm. Gated actuation using edge-aware feedback resulted in trajectory adherence rates exceeding 92%, allowing stable traversal across multi-branch vascular phantoms without wall impingement.

Interaction with Fluidic Microenvironments

The robotic system maintained positional stability across pulsatile flow regimes, with actuation synchronized to systolic phase peaks. Capacitive edge tracking minimized lateral drift and compensated for shear-induced capsule deformation. In high-shear regions—such as bifurcation necks and curvature inflections—the phased signal control preserved mechanical integrity without compromising navigational velocity. PIV imaging confirmed localized flow disruption was minimal, with recirculation zones remaining confined to sub-10 µm regions around the capsule's wake, indicating hydrodynamic compatibility with vascular hemodynamics.

Cytocompatibility and Thermal Safety Profiles

Exposure of HUVEC cultures to actuated robotic capsules revealed high cell viability (>94%) and preserved tight junction morphology, as visualized via ZO-1 immunostaining. Hemolysis assays registered less than 2% free hemoglobin release after 60 minutes of actuator operation—well below thrombogenic thresholds. Platelet activation markers (CD62P expression) remained statistically indistinguishable from control samples. Embedded thermistors recorded peak surface temperatures of 36.1°C during continuous actuation, affirming safe thermal profiles. PEG-silane surface functionalization proved effective in resisting protein adsorption, further mitigating biofouling and inflammatory responses.

Comparative Benchmarking and Operational Outlook

Compared to magnetically guided microcapsules and electrothermal swimmers, the piezoelectrically actuated system demonstrated superior responsiveness in confined geometries, with navigation latency reductions of 18–30% across tortuous microchannel layouts. System architecture favors integration into battery-less platforms powered by external acoustic or RF triggers, positioning the technology for near-term translation into intravascular diagnostics, targeted drug delivery, and microscale surgical tasks.

Conclusion

This investigation establishes nano-scale piezoelectric actuation as a viable modality for autonomous in-vivo navigation through vascular microchannels. By coupling flexural and spiral actuator morphologies with closed-loop signal gating, the system achieves steerable, high-fidelity propulsion in blood-mimetic environments—meeting both mechanical efficiency and biological safety thresholds essential for clinical translation.

The integration of edge-aware capacitive feedback enables responsive adaptation to vascular bifurcations and curvature inflections, while the soft robotic capsule architecture ensures compatibility with confined anatomical geometries. Thermal safety and cytocompatibility benchmarks underscore the technology’s potential for extended in-vivo deployment without triggering inflammatory or thrombotic responses.

Beyond immediate biomedical application, the framework sets a precedent for intelligent, topology-aware nano-robotic platforms capable of navigating structurally complex biological systems. Its

modularity invites future layering of biosensing, drug payload delivery, and molecular interrogation functions—advancing the frontier of microscale intervention and programmable therapeutic robotics.

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