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Machine Learning assisted 3D Tracking, Evaluation and Analysis of near-substrate transported Superparamagnetic Microparticles in Liquids for Sensing Applications

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The directed transport of superparamagnetic microparticles (SPPs) in a liquid medium above exchange bias-patterned magnetic stray-field landscapes is investigated using a machine-learning-assisted, three-dimensional tracking framework. A calibrated focus-sweep routine, based on the Tenenbaum Gradient, translates image sharpness into particle height, enabling sub-micron axial resolution during transport. Helium-ion-bombarded exchange-bias patterns generate head-to-head/tail-to-tail stripe domain configurations that, together with externally applied magnetic field pulse sequences, drive SPPs along trajectories close to the substrate. The system integrates open-source Tango Controls for distributed hardware management, real-time data acquisition, and visualization, while a modular machine-learning module continuously evaluates particle motion and adjusts control parameters. Results demonstrate live 3D trajectory reconstruction, velocity profiling, and automated experiment control with immediate feedback on parameter influence. The architecture supports intelligent experimentation, including real-time optimization, automatic termination upon data sufficiency, and trajectory classification. Potential applications span lab-on-a-chip sensing, analyte detection, and advanced magnetic fluid manipulation, hightlighting the platform's relevance for magnetic fluid research and technology development.

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