

Article

Detection Optimization of an Optically Trapped Microparticle in Vacuum with Kalman Filter

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Abstract: The optical trapping of micro-nano particles in a high vacuum has become a popular research platform in various frontier fields of physics because of its excellent isolation from the environment. The precise measurement of particle motion information is required to analyze and control particle motion modes in traps. However, the detection accuracy is limited by measurement noise and coupling signals from other axes in microparticle optical traps. In this study, we use the Kalman filter to extract the real motion information of each axis under simulation conditions, and the results show that the Kalman filter performs well in noise suppression, improving the RMSE from 12.64 to 5.18 nm and enhancing the feedback-cooling performance by approximately 27% through reducing the axes' signal coupling ratio. We believe that as a solution to these challenges, the Kalman filter will bring a significant achievement to micrometer particle optical traps in vacuums.

Keywords: optical trap; Kalman filter; feedback cooling; axial signal decoupling



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1. Introduction

Since Ashkin et al., used a single-beam optical trap to levitate a 20 μm silica sphere in 1971 [1], optical trapping has inspired various researches and applications in quantum physics, life science, and engineering. Trapping is developing rapidly towards smaller scales, including nanostructured trapping [2–4], on-chip optical levitation with a metalens in a vacuum [5], multiplexed near-field optical trapping [6], light polarization measurements [7], single-cell manipulation [8], on-chip protein sensing [9], and many other areas. Tongcang Li et al. used an optical trap in a vacuum to measure the instantaneous velocity of a Brownian particle [10] and to cool an optically trapped microsphere from room temperature to millikelvins [11], demonstrating the great potential of optical traps in frontier physics. Optical trapping in vacuums has also been applied to precise force and acceleration measurements and reached sub-100 $\text{ng}/\sqrt{\text{Hz}}$ and sub- $\text{aN}/\sqrt{\text{Hz}}$ spectral sensitivity while providing a much larger dynamic range than clamped resonators because of its outstanding decoupling from environment noise vibrations and gas molecule collisions [12–17]. Optical trapping, which is enabled by the ability to detect ultra-weak forces and acceleration, is expected to make a significant contribution to fields, such as searching for non-Newtonian interactions at the micrometer scale [18,19], high-frequency gravitational waves [20], and dark matter [21].

To achieve high acceleration sensitivity, the micrometer particle is more suitable than the nanometer particle because of the inverse relationship between the minimum measurable acceleration and the square of the particle radius [13]. Before the measurement process, the particle must maintain stable suspension in an ultra-high vacuum with the help of a feedback control system to suppress the Brownian motions of the trapped particle. The rapid and accurate displacement detection via photodiodes is the key part of the feedback control system. However, due to the close resonance peaks and detection coupling in microparticle optical traps [11,22], extracting the real signal requires not only considering

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