

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 ng/ $\sqrt{\text{Hz}}$ and sub-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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Table of Contents Microparticle Reagent Optimization Manual

1. Understanding the eBook Microparticle Reagent Optimization Manual
 - The Rise of Digital Reading Microparticle Reagent Optimization Manual
 - Advantages of eBooks Over Traditional Books
2. Identifying Microparticle Reagent Optimization Manual
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Microparticle Reagent Optimization Manual
 - User-Friendly Interface
4. Exploring eBook Recommendations from Microparticle Reagent Optimization Manual

- Personalized Recommendations
 - Microparticle Reagent Optimization Manual User Reviews and Ratings
 - Microparticle Reagent Optimization Manual and Bestseller Lists
5. Accessing Microparticle Reagent Optimization Manual Free and Paid eBooks
 - Microparticle Reagent Optimization Manual Public Domain eBooks
 - Microparticle Reagent Optimization Manual eBook Subscription Services
 - Microparticle Reagent Optimization Manual Budget-Friendly Options
 6. Navigating Microparticle Reagent Optimization Manual eBook Formats
 - ePub, PDF, MOBI, and More
 - Microparticle Reagent Optimization Manual Compatibility with Devices
 - Microparticle Reagent Optimization Manual Enhanced eBook Features
 7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Microparticle Reagent Optimization Manual
 - Highlighting and Note-Taking Microparticle Reagent Optimization Manual
 - Interactive Elements Microparticle Reagent Optimization Manual
 8. Staying Engaged with Microparticle Reagent Optimization Manual
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Microparticle Reagent Optimization Manual
 9. Balancing eBooks and Physical Books Microparticle Reagent Optimization Manual
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Microparticle Reagent Optimization Manual
 10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
 11. Cultivating a Reading Routine Microparticle Reagent Optimization Manual
 - Setting Reading Goals Microparticle Reagent Optimization Manual
 - Carving Out Dedicated Reading Time
 12. Sourcing Reliable Information of Microparticle Reagent Optimization Manual

- Fact-Checking eBook Content of Microparticle Reagent Optimization Manual
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning
- Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
 - Interactive and Gamified eBooks

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