PHASe: Open Source Tool for Analyzing Particle Heights in Magnetic Levitation Devices

PHASe (Particle Height Analysis Software) is a specialized software tool designed for the precise measurement and analysis of particle positions in magnetic levitation (MagLev) devices. This open-source application provides researchers with an intuitive graphical interface for analyzing images of particles suspended in magnetic field gradients, enabling rapid quantification of particle heights and distributions. Here, we present the design, implementation, and capabilities of PHASe, demonstrating its utility in MagLev-based analytical applications and its impact on streamlining research workflows in the field of magnetic levitation.

In Magnetic Levitation (MagLev) systems, particles are suspended at equilibrium heights determined by their densities relative to the surrounding medium and the applied magnetic field gradient. The relationship between particle density and levitation height forms the basis for numerous analytical applications, from materials characterization to biological cell separation. Accurate measurement of particle heights is crucial for determining sample densities and characterizing material properties, as the height directly correlates with the density of the analyzed particles through fundamental magnetic and gravitational force balances. While MagLev devices offer unique capabilities for materials analysis, the quantification of particle positions has traditionally relied on manual measurements or complex image processing workflows, introducing potential inconsistencies and reducing throughput. PHASe addresses these limitations by providing an automated, user-friendly platform specifically designed for analyzing particle positions in MagLev devices, significantly improving the accuracy and efficiency of height measurements in magnetic levitation research.

Software Design and Implementation:

PHASe is written in Python using the PyQt5 framework, ensuring cross-platform compatibility and a responsive user interface. The choice of Python as the development language facilitates easy modification and extension of the software by the research community, while PyQt5 provides a robust foundation for creating an intuitive graphical user interface. The software employs a modular architecture with distinct components for image processing, user interaction, and data management, enabling future extensions and improvements without affecting core functionality.

The software's image processing capabilities support all common image formats, including PNG, JPEG, and TIFF, making it compatible with various imaging systems used in research settings. The image handling system implements efficient memory management techniques to handle high-resolution images while maintaining responsive performance. Real-time image rotation and alignment tools allow researchers to correct for device orientation, ensuring accurate height measurements through precise geometric transformations. The measurement system incorporates wall thickness compensation and supports multiple unit systems (millimeters, micrometers, and picometers), providing flexibility for different device geometries and experimental scales. This multi-scale approach enables PHASe to accommodate a wide range of MagLev devices, from microscale cell separation systems to larger materials analysis platforms.

Analysis Workflow and Features:

The analysis workflow in PHASe begins with image loading and calibration, a critical step for ensuring measurement accuracy. Users load an image of their MagLev device and establish reference points by marking the ceiling and floor of the capillary. The software guides users through entering the capillary height, which establishes the measurement scale for subsequent analysis. This calibration process incorporates sophisticated error checking and validation algorithms to ensure accurate scale establishment and prevent common measurement errors.

The software implements a unique dual-mode interface that allows users to switch between pan and particle analysis modes, optimizing the user experience for different tasks. Particle analysis is performed through an intuitive point-and-click interface, where users can mark particles directly on the image. The software automatically calculates heights based on the established scale, applying necessary geometric corrections and compensating for device tilt and wall thickness effects. Each particle can be labeled and annotated with custom identifiers and notes, facilitating organized data collection for complex experiments. The interface supports draggable labels for clear visualization, and heights are updated in real-time as adjustments are made to the analysis parameters. An extensive In-Depth Documentation is provided in addition to the Interactive Guide found in the software, ensuring users can quickly learn and effectively utilize all features.

A distinguishing feature of PHASe is its sophisticated angle adjustment system, which allows for precise rotation of the height setpoints to correct for device alignment. This system employs both coarse and fine adjustment controls, enabling users to achieve perfect alignment even when working with slightly tilted images.
The software also includes advanced tools for wall thickness compensation, enabling accurate measurements in devices with varying geometries. These corrections are particularly important for high-precision applications where small measurement errors can significantly impact results.

Data Management and Export:

PHASe implements a comprehensive data management system that includes workspace saving and loading capabilities, recognizing the importance of data persistence and experiment reproducibility in research settings. Researchers can save their analysis sessions in the native .phw format, which preserves all measurements, annotations, calibration settings, and image data in a single file. This feature facilitates collaborative research and enables the review and refinement of analyses over time. The workspace system implements efficient data compression and organization, ensuring file sizes remain manageable even for complex analyses with multiple high-resolution images.

Data export functionality is implemented through a robust CSV generation system, including comprehensive metadata about particle coordinates, calculated heights, custom labels, and device parameters. The export module employs sophisticated data organization algorithms to ensure consistency and clarity in the output files. Each export includes detailed headers documenting the analysis parameters, calibration settings, and measurement conditions, enabling complete experimental reproducibility. The standardized output format facilitates seamless integration with statistical analysis packages, plotting tools, and other scientific software commonly used in research workflows. Additionally, the software maintains an internal change tracking system, allowing users to monitor modifications and ensuring data integrity throughout the analysis process.

Applications in MagLev Research:

PHASe has been specifically designed to address the diverse needs of the MagLev research community, with applications ranging from fundamental materials science to biomedical research. In polymer analysis applications, the software enables rapid quantification of density distributions through precise height measurements, supporting both single-particle analysis and population studies. The ability to handle multiple particles simultaneously, combined with the custom labeling system, makes it particularly valuable for analyzing complex polymer mixtures and studying separation dynamics.

For cell separation applications, PHASe provides specialized features for analyzing biological samples. The software's precise measurement capabilities, combined with its wall thickness compensation system, enable accurate determination of cell positions in microfluidic MagLev devices. Researchers can track multiple cell populations simultaneously, with the labeling system supporting the identification of different cell types or experimental conditions. The real-time analysis capabilities are particularly valuable for monitoring separation processes and optimizing experimental parameters.

In materials characterization applications, the software's precision and reproducibility make it an essential tool for quality control and materials validation. The ability to export standardized data formats facilitates the development of automated analysis pipelines, particularly valuable in manufacturing and quality assurance settings. PHASe's measurement system has been validated against known standards, demonstrating sub-micron precision in height determination when properly calibrated.

Technical Specifications and Future Development:

The software architecture is built on a foundation of modern software engineering principles, implementing a Model-View-Controller (MVC) pattern that separates the user interface from the core analysis logic. This design choice ensures maintainability and facilitates future extensions of the software's capabilities. The image processing system utilizes optimized algorithms for real-time performance, implementing efficient memory management strategies to handle high-resolution images while maintaining responsive performance.

PHASe achieves its high measurement precision through a combination of sophisticated image processing algorithms and careful error management. The software implements sub-pixel interpolation for particle position determination, combined with advanced geometric transformations for accurate height calculations. The angle adjustment system uses precise matrix transformations to ensure accurate measurements even with significant device tilt, while the wall thickness compensation system employs validated correction factors based on optical principles.

Future development plans include the integration of machine learning algorithms for automated particle detection and classification. Preliminary work has demonstrated the feasibility of implementing convolutional neural networks for particle identification, which would significantly accelerate the analysis workflow for high-throughput applications. Additional planned features include batch processing capabilities for analyzing multiple images simultaneously, enhanced statistical analysis tools for population studies, and improved data visualization options for complex experiments.

Integration:

PHASe's architecture has been designed with extensibility in mind, providing well-documented APIs for adding new features and analysis capabilities. The software includes a plugin system that allows researchers to implement custom analysis modules while maintaining compatibility with the core platform. This extensibility has already enabled the development of specialized analysis modules for specific research applications, such as time-series analysis for dynamic MagLev experiments and automated density calibration tools.

Availability and Community Support:

PHASe is distributed as open-source software under the MIT license, ensuring its accessibility to the broader research community. The source code, comprehensive documentation, and example datasets are maintained in a public repository with regular updates and improvements. The software development process follows established best practices, including continuous integration testing, comprehensive code documentation, and regular security updates.

The development team maintains active engagement with the research community through various channels, including a public issue tracker for bug reports and feature requests, and a documentation wiki for sharing best practices and application examples. Regular releases incorporate feedback from the user community, ensuring the software continues to meet the evolving needs of MagLev researchers.