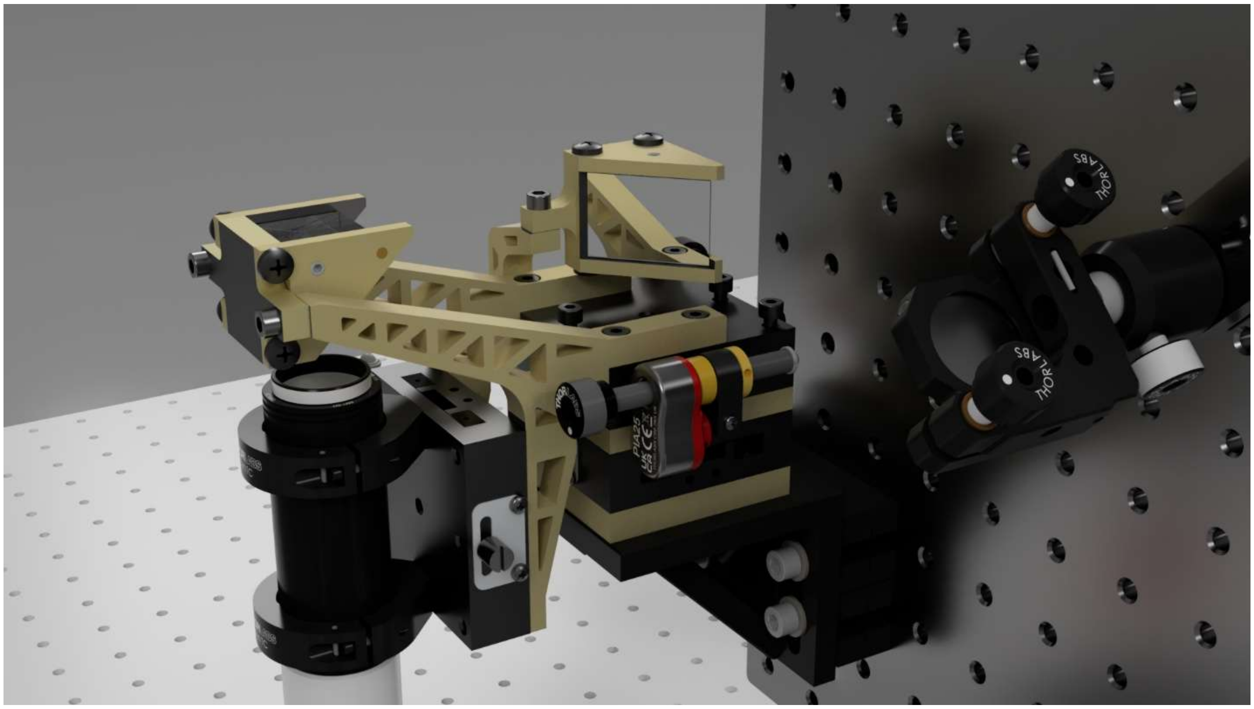

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Project Overview

The design process of the PrecisionArc Microscope (PAM) underwent multiple development phases, culminating in Version 4.5, which was the first generation to be fully integrated into a functional optical setup. PAM supports both reflected light microscopy and confocal microscopy, making it adaptable to a wide range of imaging applications. Its operation is managed through LabVIEW (National Instruments, n.d.), which communicates with the Thorlabs KIM101 controller (Thorlabs, “KIM101 Piezo,” 2015) responsible for driving the PIA25 piezo inertia actuators (Thorlabs, “PIA25,” 2015). In addition, LabVIEW interfaces with a Red Pitaya board (Red Pitaya, n.d.) via Python to process voltage signals from the photon detector, enabling precise control over both microscope motion and data acquisition.

Version 4.5, a handmade prototype built at the E5 workshop, demonstrated proof of concept by achieving 50x magnification in reflective imaging. As a handmade prototype, it exhibited slight tolerance imperfections that have been addressed in Version 4.6, which is scheduled to be machined out-of-house. This new iteration incorporates minor optimization adjustments to enhance both performance and durability. Throughout its evolution, PAM has been guided by the design principles of construction cranes, aiming for a balance between low weight, modularity, and structural rigidity.

Optical Path and Mirrors

The optical path in PAM is directed using Thorlabs MRA25 mirrors, which feature a silver coating optimized for the visible spectrum and offer approximately 95% reflectivity. These mirrors are designed for quick replacement without necessitating a complete disassembly of the system (Thorlabs, “MRA25 Mirror,” n.d.). Such ease of maintenance contributes to PAM’s overall adaptability in laboratory environments.

Applications

PAM’s versatility is demonstrated by its ability to function in quantum sensing experiments involving nitrogen-vacancy (NV) centers in diamond, enabling high-resolution imaging and optical readout of spin states critical for quantum computing and magnetometry. Its configuration also supports cryogenic imaging, providing optical access to samples inside a cryostat where conventional microscopy methods prove impractical. The inclusion of confocal microscopy makes PAM suitable for photonic device characterization, allowing for detailed analysis of photonic integrated circuits, waveguides, and other micro- or nanoscale optical components. Future adaptations may incorporate white light interferometry (WLI) for high-precision surface metrology, as well as enhancements for materials science investigations—such as reflected light microscopy for examining grain structures and defects in metals or semiconductors. While not its primary focus, PAM's confocal setup could be extended to bioimaging and fluorescence microscopy, thereby broadening its potential for visualizing labeled biological samples.

Background Theory

Reflected Light Microscopy

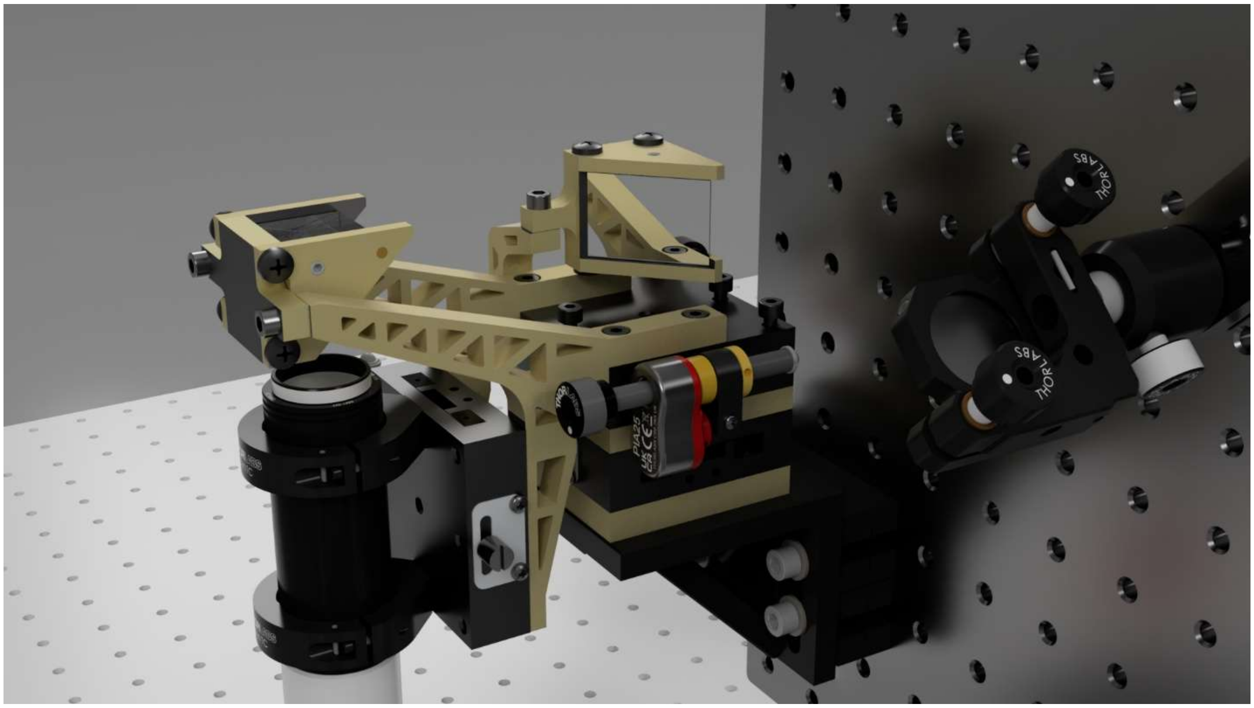
Reflected light microscopy, often referred to as incident light microscopy, is used to analyze opaque samples by illuminating them from above. The reflected light from the specimen's surface is captured by the objective lens to create an image. This approach is widely utilized in materials science, semiconductor inspection, and situations in which transmission microscopy is not feasible. In PAM, the alignment of the illumination and collection paths is optimized to maximize signal quality. High-reflectivity silver-coated mirrors direct the incident beam onto the sample and gather the reflected signal. This technique proves particularly beneficial for examining diamond samples within a cryostat, where conventional transmission methods are impossible due to both the sample's opacity and the cryostat's mechanical constraints. By refining optical components and beam alignment, PAM achieves high-contrast, high-resolution images essential for advanced optical experiments.

Confocal Microscopy

Confocal microscopy enhances resolution and contrast by selectively capturing light from a specific focal plane while rejecting out-of-focus light. Unlike standard widefield microscopy, which illuminates the entire sample at once, a confocal microscope scans the specimen point by point using a tightly focused laser beam. The collected light is then directed through an optical fiber acting as a spatial filter before reaching a photon detector. This arrangement ensures that only in-focus light is recorded, yielding sharp optical sections with minimal background noise. In an infinite-corrected confocal system, the objective lens produces parallel rays that must be refocused by an additional tube lens. Overall magnification is determined by the combination of this tube lens and any relay optics. Adjusting these components enables the system to be optimized for diverse imaging needs, such as high magnification viewing or efficient light coupling into an optical fiber for precise detection.

Mechanical Design

General Description of PAM’s Movement



Designing a crane-like system for a vertically mounted heavy objective that offers full three-dimensional control while keeping the incoming and outgoing beam paths fixed is a formidable engineering challenge. In Version 4 of the Precision Arc Imaging System (PAIS), robust support arms have been integrated to secure mirrors in precise positions. The Z-axis, which supports the objective, operates in concert with the rest of the system, moving simultaneously with both the X and Y axes. The Y-axis, in turn, is responsible for moving both a mirror positioned above the objective and the objective itself, following the motion of the X-axis while remaining independent of the Z-axis. Meanwhile, the X-axis functions as the only completely independent axis, moving the entire assembly without being affected by the movements of the other axes.

Justification for the Hanging Z-Axis Stage in PAM

In the PrecisionArc Microscope (PAM), the Z-axis stage is purposefully designed to support only the objective rather than lifting the entire system. This design choice significantly reduces the mechanical load on the PIA25 piezo slip-stick actuator, ensuring long-term reliability, precise step performance, and cost-effective operation. In open-loop piezoelectric systems, the relationship between load weight and movement consistency is determined by both the system's design and the inherent properties of piezoelectric materials. Although specific studies on open-loop piezo ratchet systems are limited, related research indicates that variations in load can affect performance.

For example, in open-loop piezoelectric actuators, the step size can vary with the applied load due to the stick-slip mechanism. As the load increases, the actuator's step size may decrease, leading to less consistent movement. This variability arises because the actuator's ability to overcome static friction is directly impacted by the load, thereby affecting the precision of each step (Newport, 2025). In the case of PAM, the PIA25 actuator has a limited force output and operates on a stick-slip mechanism. If the Z-axis stage were required to lift the entire system, it would introduce excessive strain on the actuator, reducing step consistency and increasing wear. Heavier loads make the piezo actuator more prone to missed steps, uneven movement, or increased backlash, all of which can degrade imaging quality. As noted by Thorlabs, "a higher axial load is possible, but this may decrease the typical step size or stop the actuator from driving" (Thorlabs, 2015).

By lifting only the objective, the system maintains precise and reliable step performance—an essential requirement for high-resolution microscopy. This approach allows the actuator to operate efficiently without experiencing performance degradation due to excessive weight. Ultimately, the hanging Z-axis design in PAM significantly reduces mechanical stress on the PIA25 actuator while preserving precise movement, thereby ensuring long-term durability, enhanced imaging stability, and optimized cost efficiency for high-performance microscopy.

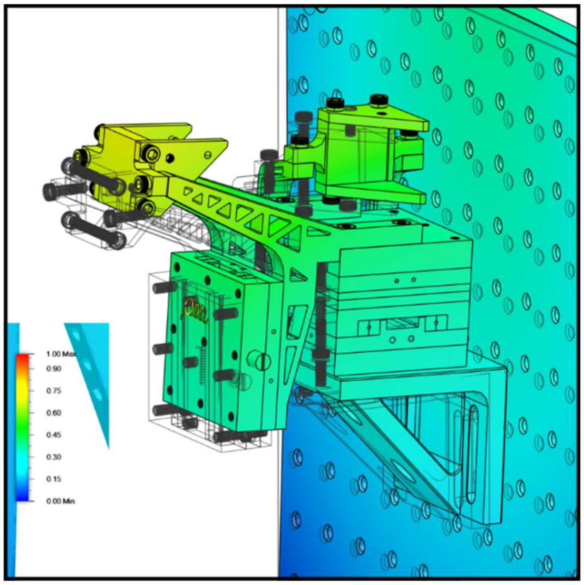
Structural Optimization: The Role of Triangular Perforations

Triangular perforations in PAM serve a dual function by reducing mass while preserving structural stiffness. This design strategy is grounded in well-established mechanical principles such as enhanced material distribution and improved modal performance—principles that have been successfully applied in aerospace and structural engineering. In this context, triangular cutouts enhance stiffness by maintaining more material away from the neutral axis, thereby increasing resistance to bending. This concept, observed in crane structures where triangular trusses achieve high strength-to-weight efficiency, is similarly applied in PAM to ensure rigidity without adding unnecessary weight.

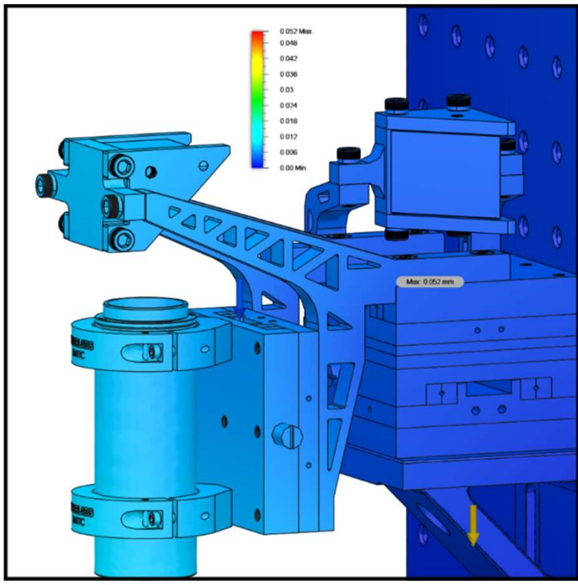
A study on microsatellite structures by Baiomy et al. found that employing triangular perforations can yield a 39% reduction in mass while still maintaining structural integrity (Baiomy et al. 1 23). Furthermore, their research indicates that the decrease in the fundamental natural frequency is minimal—ranging only from 19% to 31%—which confirms that stiffness is largely preserved despite the mass reduction (Baiomy et al. 124). The study also reported that triangular patterns offer higher modal stiffness-to-mass efficiency compared to both rectangular and isogrid configurations. Applying these findings to PAM, the reduction in inertia afforded by the perforations results in an increased natural frequency, thereby enhancing performance in applications where stability and dynamic response are critical.

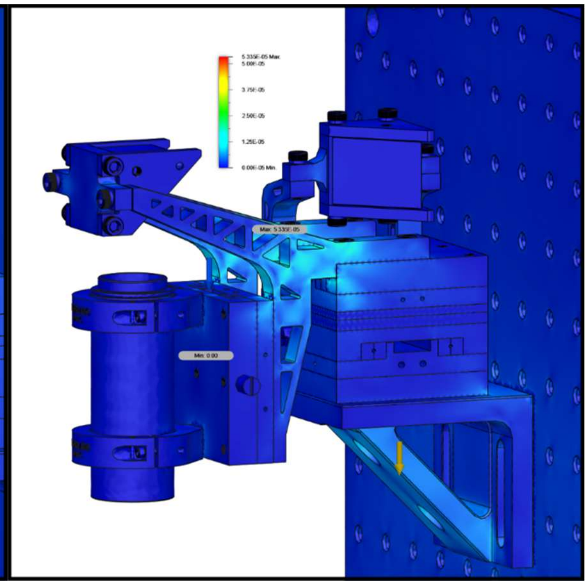
By leveraging the benefits of triangular perforations, the PAM achieves an optimal balance of mass reduction, improved natural frequency, and maintained stiffness. This design choice is especially effective for precision instruments that demand both low inertia and high mechanical stability, making it an ideal approach to optimizing overall performance.

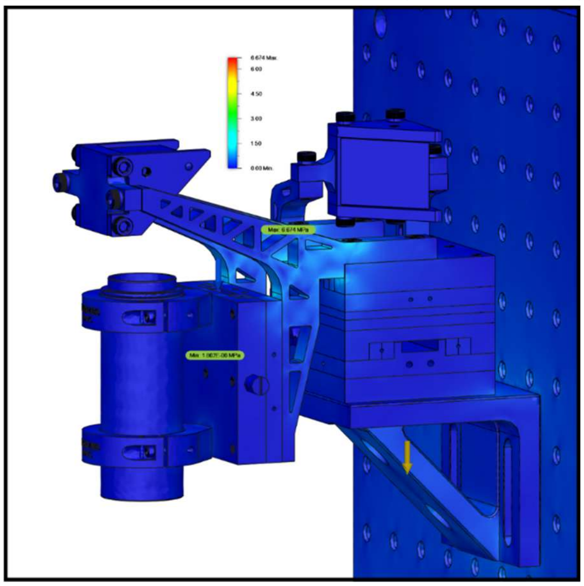
Modal Analysis



Mechanical Analysis







Hardware

The PAM system integrates several key hardware components that work together to achieve precise optical positioning.

The Thorlabs KIM101 Piezo Inertia Motor Controller orchestrates the movement of PAM's piezo-driven positioning stages. It features four independent channels that can be operated manually or remotely via USB, ensuring precise control of both the objective and mirror positions. The controller also supports external triggers such as position counting, motion activity monitoring, and limit switch activation. An integrated joystick further allows for fine control over a single axis or coordinated movement of paired axes (Thorlabs, 2015).

Complementing the controller is the Thorlabs PIA25 Piezo Inertia Actuator, which is engineered for high-precision positioning applications. This actuator employs a stepping mechanism driven by voltage pulses that induce minute rotational movements in a threaded drive screw, translating into linear displacement. Under typical operating conditions, the step sizes range from 10 to 30 nm, though variations of up to 20% may occur depending on the load. Its capability to maintain position without a continuous power supply makes it ideally suited for the exacting demands of the PAM system (Thorlabs, 2015).

The T60X-25C/R translation stage from MPositioning Co., Limited is engineered to provide smooth, precise motion along a single axis. With a travel range of ±12.5 mm and a 60 mm x 60 mm platform, this stage is well suited for optical alignment tasks requiring fine positional control. The stage employs a micrometer head with a 0.50 mm pitch and relies on crossed-roller bearings to minimize friction and ensure consistent movement. Constructed from black-anodized aluminum alloy, the stage measures 18 mm in thickness, supports loads of up to 5.0 kg, and maintains a moving flatness of under 0.003 mm. Weighing approximately 0.30 kg, the T60X-25C/R strikes an optimal balance between durability, precision, and ease of integration into various experimental setups (MPositioning Co., Limited, n.d.).

Software

PAM is controlled using LabVIEW, a graphical programming environment that interfaces with the KIM101 to provide precise and customizable control over the microscope's movements. This flexibility enables the integration of advanced imaging tools, including automated mapping and sample imaging. One key feature is the ability to stitch multiple images together to create a large-area surface map, facilitating rapid location analysis for experimental planning.

In addition to surface imaging, PAM's software suite includes a confocal raster scanning module. This operates similarly to the mapping function but utilizes confocal microscopy principles to capture high-resolution optical sections. The confocal scans provide detailed 3D reconstructions of sample structures, improving data quality for quantum and nanophotonic research applications.

(SUPERSCRIPT REFERENCING WILL BE ADDED TO CONNECT BACK TO PREVIOUS SECTIONS ON THEORY)

(The moving flatness should be addressed in the software as fixed. Basically correct the Z-axis as you scan X-Y).

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