Orthogonal Laser Metrology Module (O-LAMM)

Malcolm Humphrey, Pu Fan
PLX Inc, 40 West Jefryn Blvd. Deer Park NY, 11729, USA

ABSTRACT

PLX's Orthogonal Laser Metrology Module (O-LAMM) integrates core Monolithic Optical Structure Technology™ (M.O.S.T) [1] and precision Beam Steering Technology [2], creating a compact and robust 3D laser-scanning system for in situ metrology. The O-LAMM generates a laser line directed into a scanning mirror system, scanning multiple targets at high speeds of 100 Hz using retro-reflective cooperative markers on robotic end-effectors. The system captures X and Y locations upon laser-retroreflector interaction, and through triangulation with a second O-LAMM unit at a known distance, it enables Z location determination. By networking multiple O-LAMMs, blind spots within a target volume are minimized, providing a full specification 6-DOF high-precision position measuring device. This innovative solution is an essential component for adaptive manufacturing and Industry 4.0 applications, maintaining arc second accuracy through the integration of multiple systems while offering speed and flexibility across a wide range of measurement-related tasks in production lines. The O-LAMM system is well-suited for testing, inspection, positioning, deformation analysis, and tracking applications, delivering unmatched high-speed geometric data collection and Intelligent Manufacturing System (IMS) applications.

Keywords: Orthogonal Laser Metrology Module (O-LAMM), PLX, Laser-scanning, Laser guided industrial robots, Beam steering, Monolithic Optical Structure

1. INTRODUCTION

Founded in 1955, PLX has been manufacturing highly precise optical components, such as domes, lenses, prisms, and mirrors. With the development of Monolithic Optical Structure Technology™ (M.O.S.T.), PLX has expanded its scope to active optical metrology systems, addressing next-generation optical requirements for Intelligent Manufacturing Systems (IMS) [3] applications in Industry 4.0. The Orthogonal Laser Metrology Module (O-LAMM) is a sophisticated 3D laser-scanning system for in situ metrology.

Utilizing PLX's precision beam steering technology and M.O.S.T., the O-LAMM system employs a scanning mirror system and retro-reflective cooperative markers on robotic end-effectors, enabling high-speed geometric data collection at 100 Hz across various measurement-related applications in IMS production lines. The evolution from the First Generation 1D scanning Laser Metrology Module (LAMM) to the Second Generation O-LAMM has led to the integration of PLX monolithic optical structure technology with active optical elements such as beam steering mirrors, light sources and detectors.

The O-LAMM system captures X and Y locations upon laser-retroreflector interaction, while triangulation with a second O-LAMM unit enables Z location determination. Networking multiple O-LAMMs minimizes blind spots, providing a full specification 6-DOF high-precision position measuring device. The O-LAMM system holds promise for optimizing asset performance management in Industry 4.0 and becoming an essential component of smart manufacturing strategies. Its adaptability to various manufacturing environments ensures its value as a solution for modern industrial applications, contributing to the efficient and precise operation of intelligent manufacturing systems.

2. FROM LAMM TO O-LAMM

2.1 The fundamental working mechanism of 1D scanning Laser Metrology Module (LAMM)

The depiction of LAMM elucidates the basic working principle of this laser metrology system, which utilizes 1D scanning based on a single-axis scanning mirror device, such as a Microelectromechanical Systems (MEMS) or Galvo mirror. The 1D LAMM is an active optical system that integrates electrical hardware, software, and firmware to scan a laser dot in a line, detecting the reflected signal when the beam encounters an optical retroreflector.

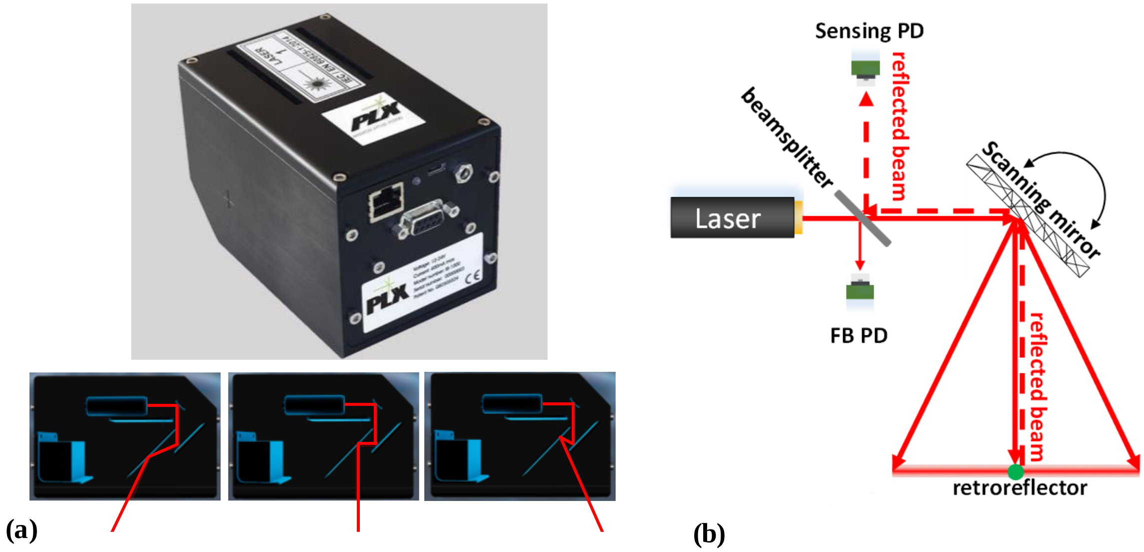

Figure 1. (a) The upper image showcases the G1-LAMM device, engineered by PLX INC, with the lower row of animated images illustrating three distinct scanning configurations achieved by adjusting the angles of the exposed LAMM's scanning mirror. (b) A schematic diagram of the one-dimensional (1D) scanning Laser Metrology Module (LAMM) demonstrates the interplay of key components, including the feedback (FB) mechanism and the photodetector (PD).

In the upper section of Figure 1(a), a photograph of the LAMM device, constructed by PLX INC, is displayed. The lower row of images in Figure 1(a) demonstrates three representative scanning. The schematic diagram in Figure 1(b) reveals that a collimated laser beam serves as the light source. A beam-splitter directs a small portion of the light to a photodiode, while the majority of the light is channeled to a scanning mirror driven by a beam steering device, utilizing PLX's distinctive techniques [2]. Within the 1D LAMM's scanning field, a single reflector is depicted as a green dot at the center of the scanning line. A dashed red line illustrates the retroreflected light's trajectory, which aligns precisely with the path of the original incident beam. Beneath the scanning line, the time axis portrays the sequential signals received by the Feedback (FB) Photodetector (PD) and the sensing PD.

The primary objective of this design is to correlate the time at which the laser impinges on the retroreflector to mirror angle at the time of reflection. Considering the significantly high speed of light and the distance between the sensing and FB PDs in the order of meters, it is reasonable to assume that the laser beam impinges on these two types of PDs concurrently. Given the known angular speed of the steering mirror as ω, the angle of θ, representing the mirror angle at the time of reflection, can be computed as follows:

$$\theta = \omega \bullet \Delta t, \tag{1}$$

where Δt denotes the time interval between the instance t0 at the start of the scan and the time when the sensing PD receives the retroreflected signals. As illustrated by the time axis in Figure 1 (b), Δt can be defined as $0.5 \bullet (\boldsymbol{t_1} + \boldsymbol{t'_1}) - t_0$ in this particular case, with the assumption that the signal pulse is simplified as a square waveform. In reality, the time-resolved retroreflected signal obtained by the sensing PD typically exhibits a Gaussian distribution. Under such circumstances, Δt may be determined using an alternative algorithm rather than taking the average. Nonetheless, the underlying mechanism serves as the fundamental physics for converting the temporal information recorded by the system into spatial distribution.

2.2 Two-Dimensional (2D) Laser Metrology: Orthogonal Laser Metrology Module (O-LAMM)

Orthogonal Laser Metrology Module (O-LAMM): Building upon the LAMM concept, the technology has been advanced to enable two-dimensional (2D) laser metrology. One of the critical innovations within the O-LAMM system is the shift from using a single laser dot scan to employing a laser line scan for positioning retroreflectors. This change allows the O-LAMM to accurately locate targets within a 2D conical region using 1D scanning techniques. The laser line scan covers a larger area in a single sweep, allowing for more efficient data acquisition and improved target location accuracy compared to the traditional laser dot scan method. Unlike typical laser metrology technologies that rely on photogrammetry or laser tracking, the O-LAMM system is able to operate within as a closed-loop positioning system improving overall accuracy and performance of the host system.

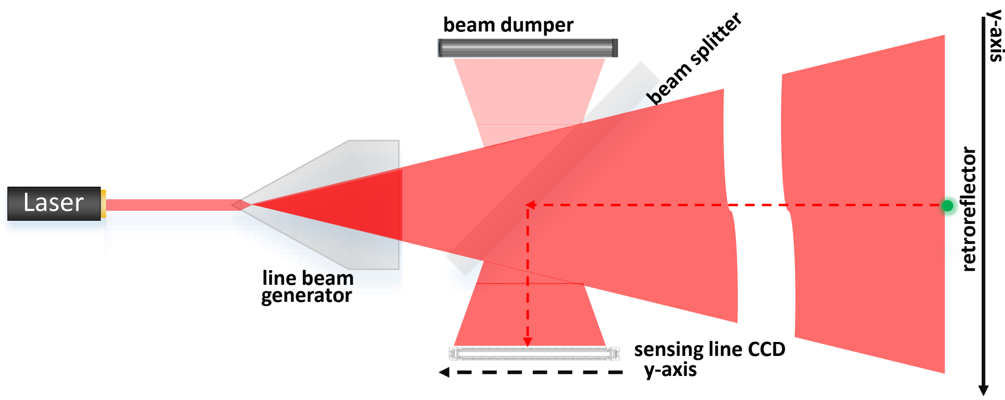

Figure 2. Schematic diagram of Orthogonal Laser Metrology Module (O-LAMM). O-LAMM scans a laser beam line to achieve two-dimensional (2D) locations of targeting retroreflectors.

The innovative approach of using 1D scanning for 2D positioning is made possible by incorporating an optical component, the line beam generator. This component can either be a cylindrical lens or a Powell lens. In this design, the Powell lens was chosen due to its significant improvement in line generator performance compared to a cylindrical lens. It is a known limitation that the illuminated line produced by a cylindrical lens is non-uniform and Gaussian in nature.

Figure 2 displays the simplified schematic diagram of O-LAMM system excluding the part of 1D scanning design to achieve x-axis positioning using temporal measurements, which was iterated in detail in section 2.1. Similar to LAMM, O-LAMM also utilizes 1D scanning which direction is perpendicular to the paper plane in the configuration of figures.

In the O-LAMM system, the line beam produced by the Powell lens is divided into two paths by a beamsplitter. When the primary optical path of the line beam, perpendicular to the scanning axis, encounters a retroreflector, the reflected light is directed back to a line sensor, represented by the dashed red line, while the unused path is terminated by a beam dumper. The reflected light striking different positions on the line sensor corresponds to distinct angles within the scanned laser line. This spatial relationship enables the determination of y-axis positioning in the 2D metrology system.

To assess the feasibility of the O-LAMM system, OpticStudio, an optical design program developed by Zemax, was employed. The software was used to simulate the optical geometry necessary for determining the positions of target retroreflectors based on their reflected signals acquired by a line CCD.

In the simulation, the actual parameters of the optical components and devices used in the design were incorporated to ensure an accurate representation of the O-LAMM system. This process was crucial in verifying the system's feasibility and performance capabilities.

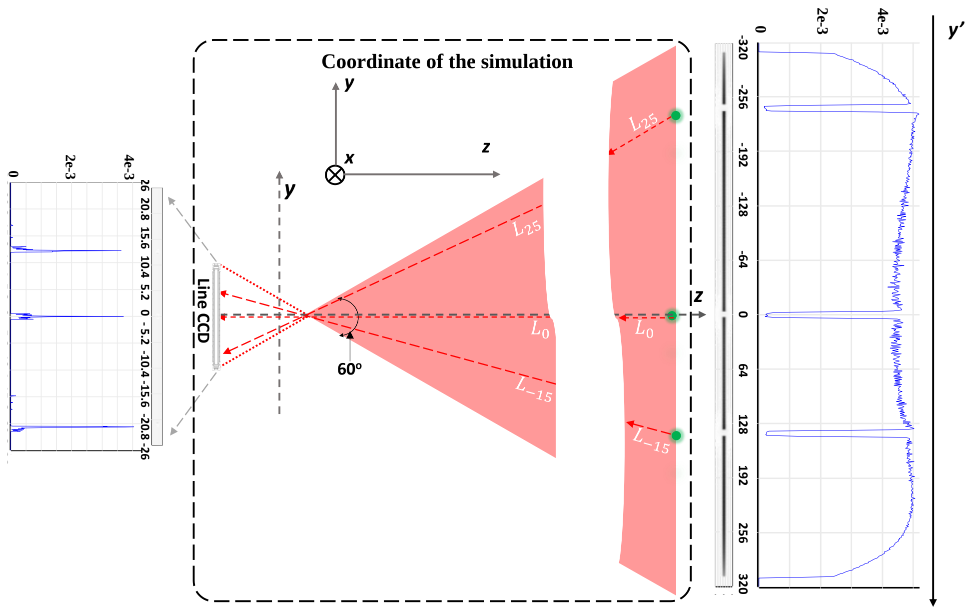

Figure 3. The results obtained by OpticStudio simulation, and the simplified optical geometry illustrate mechanism of the *y*-axis location for our O-LAMM system, and the simulating conditions applied in this study.

The simplified optical geometry illustrating the y-axis positioning mechanism for the O-LAMM system, as well as the simulation conditions used in this study, are presented within the central dashed-line rectangle in Figure 3. Three retroreflectors are positioned at -15°, 0°, and 25° relative to the z-axis. The laser beam, spanning 60° through the Powell lens (not shown in the figure), is represented as a light red fan-shaped area. When the line beam intersects with the three retroreflectors, the corresponding beam segments are reflected along the same path but in the opposite direction. The dashed lines representing the reflected beams, L-15, L0, and L25, correspond to the beams reflected by the retroreflectors at -15°, 0°, and 25°. The line CCD records the reflected signals, while another rectangular detector positioned behind the retroreflectors is utilized to validate their positions.

The simulated images captured by both detectors are represented in Figure 3 as left and right columns, corresponding to the imaging and actual positions, respectively. The y-axis locations can be visualized and quantified by examining the spatial intensity profiles of the images, obtained by selecting the central line of the strongest beam.

It is evident that the y-axis positions of the retroreflectors in the imaging coordinate (peak positions in the leftmost graph) are linearly proportional to the corresponding positions in the actual coordinate (valley positions in the rightmost graph) relative to the intercept of the starting point of the spanning beam-fan. The retroreflector positions in the imaging plane are indicated by the peaks, as the laser beam intensities are reflected by the retroreflectors.

When multiple O-LAMM systems are set at known positions within the measurement environment, the triangulation process for determining the z-axis of the target retroreflectors becomes more robust and reliable. Having precise coordinates of the O-LAMM units allows for a more accurate calculation of the geometric relationships and intersection points between the line-of-sight vectors originating from each O-LAMM. This setup not only enhances the accuracy of the 3D metrology system but also ensures greater repeatability and consistency in determining the three-dimensional coordinates of the target retroreflectors in the measurement space.

3. DISCUSSION

In this paper, we have presented preliminary results of a simulation study that validates the feasibility of O-LAMM, developed by PLX Inc., for 2D angular measurements using 1D scanning of a line beam, based on the established LAMM product. Conventional metrology systems for industrial applications typically employ photogrammetry or laser tracking, which are designed primarily for measurements rather than real-time closed-loop control, limiting their utility in real-time controlling applications due to processing and communication latency.

Our O-LAMM design is a novel design that combines 1D scanning, line beam generator, with a single-axis steering mirror and a high-resolution, high-speed line sensor to scan a volume. The system enables real-time feedback to correct the motion of robots or mechanical systems. Accurate timestamping ensures the precise timing of each reflector position detection.

Leveraging the core M.O.S.T technology developed by PLX, it is possible to integrate two O-LAMM systems while maintaining arcsecond accuracy. The second O-LAMM system, positioned at a known distance from the first, facilitates the capture of z-axis information through triangulation, as the x, y, z coordinates of both systems are known. Multiple O-LAMM systems with constellations of multiple reflectors can be seamlessly networked to reduce or eliminate blind spots within a target volume, allowing for accurate determination of target position and pose (6 Degrees of Freedom).

4. CONCLUSION

In conclusion, we have presented the construction of LAMM products and the development of the O-LAMM system, which is a novel laser metrology device utilizing a single axis scanning of a line beam to achieve 2D angular measurements. O-LAMM is capable of determining the angle at the scanning direction (x-axis) by converting detected temporal signals and the angle at the beam spanning direction (y-axis) by analyzing the geometry of optics from the reflected beam falling on different positions of the line sensor corresponding to different angles within the scanned laser line. The feasibility of O-LAMM was validated through OpticStudio simulations, which demonstrated good agreement between the retrieved angles and the known parameters of the objects defined in the simulation. The approach is applicable to 2D geometries and can be extended to 3D applications by integrating multiple LAMM devices for real-time metrology, enabling the determination of the range of a target and its lateral position. The advantages of O-LAMM include a balance of cost and precision in comparison to current systems for industrial metrology applications. Additionally, the integration of O-LAMM with the unique techniques of M.O.S.T has the potential to provide vital real-time information required for closing the loop in Adaptive manufacturing and underpinning industry 4.0.

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